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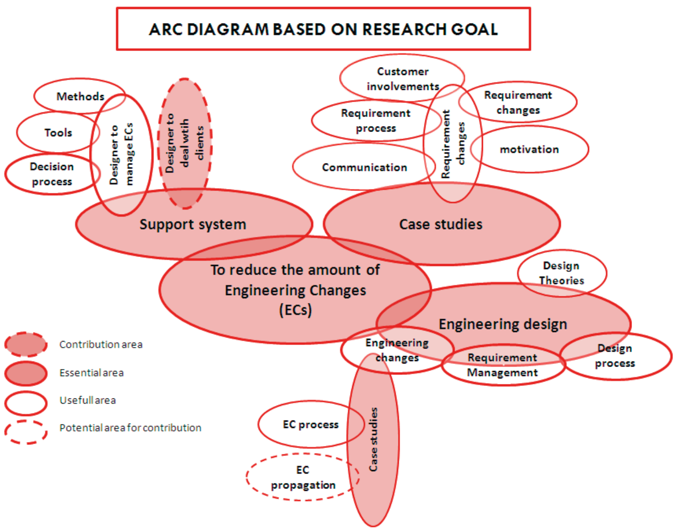

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DTU Management Engineering

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DTU Management Engineering
Department of Management Engineering

Understanding the Nature of Specification Changes and Feedback to the Specification Development Process

PhD Thesis

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Preface

This thesis is submitted as partial fulfillment of the requirements for Doctorate degree (PhD) at Technical University of Denmark (DTU-Denmark Tekniske Universitet), Kgs. Lyngby, Denmark. The PhD started on the 15th of November 2007 and was carried out at Department of Management Engineering, DTU. The research was funded by Universiti Teknikal Malaysia Melaka (UTeM) and Malaysia Ministry of Higher Education (MOHE). Associate Professor Saeema Ahmed-Kristensen was the supervisor for the project. Core research activities-i.e. document analyses were carried at the DTU Management and interviews were carried out at Institute of Product Development, DTU.

Firstly, I am in debt and utmost grateful to my supervisor, Saeema for following this research from the very beginning to its completion. Thank you for your support and significant contributions to my needs during the long hours. Secondly, I would like to record my special thanks to my parents and my siblings for their continuous support and pray in these few years. Also special thanks to my wife Khatijah, my daughters, Aqilah and Atiqah and my son Ahmad for their understanding, love and always make me happy.

I had also received numerous helps and support from my Malaysian fellows in Denmark and friends especially Kama, Zana, Nazrul, Abdillah, Detlef, Adrian Tan, Azliner, Jonas, Ole, Giovanna, Nadja, Vinicius, Dayang, Azizul, Fadzli, Ala, Akma, Syuren, Sarah and Sue for their assistance and morale support and sharing of their knowledge during this endeavor. For this I am utmost grateful.

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Abstract

Today's competitive market has created an extremely challenging environment for global businesses. The challenges for the companies as to remain competitive are cost and time to market but at the same times able to maintain or increase the quality of product to the highest level. To react to these challenges the reasons for higher cost and delay of time to market must be identified at first and strategies for lead-time reduction must be implemented afterward. In business perspective, a new, more strategic outsourcing model could be necessary for speeding for time to market yet also limiting the development cost of new product. In the product development perspective, organizing the tasks in complex design project is essential as repeating the same tasks due to Engineering Changes (ECs) as the product being developed is one of the reasons for the longer lead-time. Thus, reducing the numbers of Engineering Changes (ECs) could be promising in reducing lead-time.

The underlying reason for ECs is changes in specification and these changes are carried out for two objectives namely product improvement or error rectification. ECs occur at any stage of the product development process. As ECs are normal part in the product development process thus good Engineering Changes Management (ECM) practice and developing a better design specification is necessary at the start of the product development process. This research study focuses on the effort to develop a better design specification at the start of the product development process. Thus the objective of the research has two fold: 1) Understanding; the significance of changes in specification to ECs during the product development process; the specification development process, the activities carried by design engineers to clarify the design problem and; 2) Developing a practical design support to facilitate design engineer to formulate better requirements for a product. To support the 'understanding' objective, three studies were carried out namely: 1) Study 1-document analysis of change request reports (271 reports): 2) Study 2-evolution of requirements during the design process for new product version (6 interviews) and; 3) Study 3-problem decomposition during the specification development process (document analysis of 3 specification documents).

The contributions of the research study are on the following:

- Provide an insight about the nature of changes in specification during the product's lifecycle.
- Provide empirical evidence about the signification of a specification throughout the product's lifecycle
- Provide an insight about the development of a specification, evolution of requirements during the design process and consideration made by design engineers as they formulate requirements for a specification.
- Provide a method to consider issues and formulate better requirements for a specification at the start of the product development process.

The results of the research study shows that the development of a better design specification at the start of the design process is significance for ECs reduction as ECs due to changes in specification contributed 13 % - 40 % to ECs occurrence during the product's lifecycle. In addition, the capability of design engineers to clarify the design problem by decomposing an issue is an advantage for formulating a better requirement.

The thesis is concluded with the conclusion of the literature review, Descriptive Study I (DS I), Prescriptive Study (PS) and the evaluation of design support. Future recommendations on how to further improve the devised design support and research area about the specification is included as well, such that the design support can be push to meet the industrial needs.

Danske Resumě

Det konkurrencepræget marked der eksisterer i dag har skabt store udfordringer for globale virksomheder. Disse udfordringer er relateret til økonomi og tid til markedet men også på same tid at opretholde og forøge kvaliteten af produktet så meget som muligt. For at reagere på disse udfordringer skal baggrundede til højere omkostninger samt forsinkelser i produktudgivelser identificeres og strategier for at adressere disse skal derefter implementeres. Set i et forretningsperspektiv kan en ny og mere strategisk outsourcing model være nødvendig for at kunne nå markeder samtidig med at omkostninger ved produktudvikling holdes nede. I et produktudviklingsperspektiv er organisationen af opgaver i et komplekst design projekt essentielt idet at gentagelse af de same opgaver grundet Engineering Changes (ECs) mens produktet bliver udviklet er en af grundede til forsinkelser i produktudgivelser.

Den underliggende grund for ECs er forandringer i specifikationer og disse forandringer sker på grund af (1) produkt forbedring samt (2) fejl rettelse. ECs sker på ethvert stadie af produktudviklingsprocessen. Da ECs er en normal del af produktudviklingsprocessen er god Engineering Changes Management (ECM) praksis og udviklingen af en bedre design specifikation nødvendigt i starten af produktudviklingsprocessen.

Dette forskningsstudie fokusere på at udvikle en bedre design specifikation i starten af produktudviklingsprocessen. Der er to forskningsobjektiver 1) Forståelse af betydningen af forandringer i specifikationer til ECs i produktudviklingsprocessen; specifikations udviklingsprocessen samt aktiviteterne som udføres af design ingeniører for at klargøre design problemer og 2) Udvikling af praktisk design støtte til at facilitere design ingeniører til at formulere bedre kravspecifikationer for et produkt. For at støtte 'forståelse' objektivet blev 3 studier gennemført. Disse var: 1) Studie 1 – dokument analyse af produkt forandrings forespørgsler (271 reporter), 2) Studie 2- evolution af krav specifikationen i design processen for ny produkt udvikling (6 interviews) og 3) Studie 3 - problem dekomposition i krav specifikation udviklings processen (dokument analyse af 3 krav specifikations dokumenter).

Dette forskningsstudie har bidraget med:

- Indsigt ind i hvilke forandringer der laves i specifikationer igennem produktets liv.
- Empirisk bevis på betydningen af en specifikation igennem produktets liv.
- Indsigt ind i udviklingen af en specifikation, evolution af specifikationer i designprocessen og overvejelser foretaget af design ingeniører når de formulerer krav til en kravspecifikation.
- En metode til at adressere forskellige problemer og formulere bedre krav til en specifikation i starten af produktudviklingsprocessen.

Resultaterne af dette forskningsstudie har vist at udviklingen af en bedre design specifikation i starten af design processen signifikant reducere ECs da forandringer i krav tæller for 13-40 % af ECs igennem produktets livstid. Derudover blev det vist at det er en fordel med hensyn til at lave en bedre krav specifikation at design ingeniører kan tydeligøre et design problem ved at dekomponere det.

Denne afhandling består af en litteratur undersøgelse, et Deskriptivt Studie I (DS I), et Præskriptivt Studie (PS) og udviklingen af et design støtte værktøj. Forslag til videre forskning samt videre udvikling af design værktøjet er detaljeret så dette kan møde industrielle behov.

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CHAPTER 1: INTRODUCTION

1.1 Business challenges and feedback to the design process

Today's competitive market has created an extremely challenging environment for global businesses. Time-to-market and product development costs are some of the key measures of product development companies. To remain competitive, companies are under pressure to reduce the lead-time and cost, but at the same time to try to maintain or increase the quality of products at the highest levels. In addition, there is a high demand for efficiency, and hence an ability to adapt to these situations is essential. This ability is increasingly critical due to changes in and pressures on product development such as increasing complexity, worldwide competition, shorter product life cycle, new product liability regulations and increasing consumer-awareness [Blessing 1996]. Thus, the challenges to the companies are to make products (e.g. systems, machines, devices, tools) better, cheaper and quicker because only the fastest and the most productive can remain competitive. To meet these demands, changes ranging from large re-organisations to the development of process models for product development, or the deployment of support tools, are needed. In a company, the functional area that is facing continuous challenges concerning environmental demands, quality demands, new technology, etc. is the product development process. Thus, the continuous improvement of both the process and the product has become essential in order to remain competitive. The effectiveness and efficiency of an existing design process has to be improved. Therefore, improving the design process during the product development has been the focus of companies and researchers in engineering design [Blessing 1996; Blessing and Chakrabarti 2009]. The results of the design process have a significant effect on the cost and quality of a product [Ullman 2003]. It was estimated that more than 75% of a product's cost is locked-in at the end of the conceptual design phase [Lemon *et al.* 2001; Ullman 2003]. The capability to improve the design process will increase the competitiveness of companies because it will also contribute to the quality of the product. Therefore, to survive in a global business, improving the design process must be one of the main agendas of a company.

Customers’ expectations over the characteristics of the product they buy have been increasing. Hence, industries are struggling to keep pace with the customers' expectations. Customers’ requirements are elicited during the task clarification process. The task clarification process is the first and most valued stage in the design process. At the end of this process, accurate requirements of the target performances for a desired product are defined and explicitly written in a medium named a ‘specification document’. These requirements set up the boundaries to the solution space within which the design engineers must search [Cross 2000]. These requirements are also used to evaluate the on-going solution in the later phases. Defining the requirements at the start of the design process is essential [Pugh 1997; Ulrich and Eppinger 2000; Pahl and Beitz 1996], in order to verify that the characteristics of the product meet the customers’ expectation. Thus, the task clarification process is the area that needs improvement in order to have well defined requirements.

Improving the task clarification process is of benefit to industries in terms of lead-time and cost. Almost 40% of the manufacturing cost of a typical product is committed by the end of the task clarification process [Ullman 2003]. One of the main competitive advantages of Japanese car makers over Western car makers in producing "high quality" products in shorter lead times is due to their focus on the requirements development process [Ward *et al.* 1995]. Yet, the process of designing appropriate performance requirements does not get enough attention in practice and theory [Roozenburg and Dorst 1991]. Therefore, the first step towards improving the design process is to improve the task clarification process. Hence, this is the focus of this research study. The detailed scope of this research study is described in the next section.

1.2 Setting the scene: Motivation behind the research

A product is developed with the intention to succeed in the market. The quality of a product depends on the quality of work of the design engineers. The work of design engineers is influenced by several factors at the lower levels. These lower factors comprise a systematic design process, technical knowledge of the product designers, clarity of tasks, well defined problems, clarity of procedures, teamwork, front loading practice, effective communication, etc. [Hales 2001]. Some determinants to the success of the products are the number of recalls, the level of requirements attained, the level of customer acceptance, etc. These determinants are related to the quality of the product. Thus to remain competitive, companies struggle to improve the quality of the product or at least to keep it. Companies redesign the product for improvement. Extra features are added, and design flaws are removed. This is done through the Engineering Changes (ECs) process, resulting in a new version or variant of the product to be produced.

ECs are a normal part in the product's life cycle. Almost all products are based on other product ideas or from other designs. Thus, all designs are ECs [Eckert *et al.* 2003]. ECs are changes to products, to drawings, to prototypes or software that have been released [Terwiesch and Loch 1999]. ECs occur in every life cycle phase of a product and every step in the product development process [Köhler et al. 2008]. ECs were classified based on the relation between the new and prior product [Eckert et al. 2003]. Innovation ECs occur primarily during the planning stage and feasibility stage of the design process. Developmental ECs are split into two; initiated changes - occurring in response to external factors i.e. new customer demand or legislation, and emergence changes - occurring in response to the problem with the product. Operational ECs occur after products have long been delivered to customers. Within the same version of the product, ECs do exist as the product progresses along its life cycle phase. Around 76% of ECs are during the manufacture/build & testing phase, 8% during the development phase and 16% during the service phase [Ahmed and Kanike 2007]. These changes are related to developmental and operational ECs. ECs cause disruption to the normal product development process. ECs consume time and cost. The cost for ECs once production has started can exceed USD 150, 000 per change (on average), before production - in the build and test phase the cost is USD10-20,000 per change (on average), and in the design phase the cost is USD1000-USD2000 per change (on average) [Lemon *et al.* 2001]. Overall lead-times exceed the pure problem solving time by a factor of 10 or more due to ECs [Loch and Terweisch 1999]. Reducing the number of ECs during the product development process could benefit the industries as it contributes to a more efficient design process.

There are many reasons for ECs. Changes in requirements are amongst the major reasons [Ahmed and Kanike 2007]. Changes in requirements are needed to initiate the design process and are necessary at the planning stage to derive innovation (innovation

ECs). If changes in requirements exist in the later phase, this shows that the requirements in a specification have some deficiencies. Deficiencies in the requirements may cause disruption to industries through enormous waste of effort, resources and materials as well as the bankruptcy of the original vertical lift unit manufacturer [Hales 2001]. The requirements can be vague or overly ambitious, and a mismatch between the perspective of the customers and the design engineers may be an issue. The requirements may impose a false constraint. In all circumstances, changes in requirements are due to its deficiencies. These deficiencies can be reduced by formulating good requirements in the initial design phase.

The level of deficiencies can be determined through the number of changes in the requirements. The number of ECs due to requirement changes influences the design process as the ECs consume time and cost. Reducing the number of requirement changes is an approach to reduce the number of ECs, eventually improving the design process. To improve the design process, the requirements in a specification should be precise as this will reduce the number of requirement changes. There is insufficient empirical evidence about the relationship between requirements and the quality of a product. Empirical evidence is necessary to describe the effort to improve the design process through improving the quality of the requirements in a specification. Thus, an analysis of ECs due to requirement changes could provide empirical evidence about the significance of developing better requirements in a specification as part of the task clarification process. Hence, this is one of the focuses for this research. In addition, the study of the task clarification during the product development process will be a part of this research study.

1.3 Scope of the research and research questions

A specification is a central part of the product development process. Specifications establish a basis for designing tasks during the product development process. An output of this process is a product. In the course of this process, ECs will occur. A systematic analysis of the product development process usually reveals the factors leading to ECs. Directly relating the quality of a specification to the quality of a product is not possible as many factors contribute to the occurrence of ECs over and beyond changes in a specification. During the product development process, a combination of human activities is required to produce a product, which may contribute to the occurrence of ECs. One dimension which can be used to assess the quality of a specification is to look at the number of ECs caused by requirement changes. Changes to these requirements show that they had some deficiencies and therefore there is a need for revision. Hence, this can provide empirical evidence for the need for better requirements in a specification at the start of the product development process. This research study will examine the nature of requirements in a specification from the perspective of ECs. Thus, the focus of this inquiry is on the ECs that are associated to changes in requirements. In addition, the study will also explore the current practice of the requirements formulation process. The scope of this research study is on the requirements that have been specified in a specification. All verbal requirements that are not specified in a specification are out of the scope of this research.

The specific objectives of this research project are:

- To provide empirical evidence about the influence of changes in requirements on Engineering Changes (ECs) occurring during and after the original design task has been completed.
- To understand the specification development process employed by design engineers when developing requirements for a specification
- To understand the process carried out by design engineers to understand the design problem.
- To develop practical support to facilitate design engineers to decompose the design problem and to formulate requirements in a specification.

1.4 Research aims and research questions

The research aims at both: Understanding the product development process, comprising understanding Engineering Changes (ECs) that are associated to requirements change, and understanding the development of requirements at the start of the product development process; and developing effective design support to assist design engineers to formulate requirements. This support aims to reduce requirement deficiencies and finally to mitigate changes in requirements during the product development process especially for late ECs (once the design process is completed).

This research study has two main research questions and six sub-questions. These are:

1). **Overall research question 1:** How do Engineering Changes (ECs) that are a result of changes in requirements, affect the product development process and provide feedback to the development of the specification document?

Sub-research questions:

- How significant is the impact of changes in requirement towards Engineering Changes (ECs) during the product's life cycle?
- What can be learnt from changes in requirement in order to develop a better specification (specification with fewer changes) at the start of the product development process?
- How is the development of a specification carried out for a project?

2). **Overall research question 2**: How can we ensure that all the important design issues are addressed and translated as requirements in a specification?

Sub-research questions:

- How do specification developers formulate requirements for a specification?
- What is the process undertaken by design engineers to understand the design problem at the start of the product development process?
- How do design engineers address and translate the design problem to a list of requirements for any one project?

1.5 Thesis structure

The structure of this thesis is presented in Figure 1.1. The six chapters and appendices can be summarised as below:

Chapter 1: Introduction

This chapter provides the motivation for the research study, scope of research, aims and objectives of research. Also the structure and terminology used in this thesis is presented.

Chapter 2: Literature review

This chapter presents a review of the literature in the main areas namely; design methodology, design specification and Engineering Changes (ECs). The conclusion of each topic is included and their relation to the research study is highlighted.

Chapter 3: Research methodology

This chapter explains the methodological approaches, Design Research Methodology (DRM) framework, data collection, and the data analysis methods adopted in the three studies carried out in the descriptive study phase of the research study.

Chapter 4: Results of descriptive studies

This chapter presents the results of the three studies carried out in this research. All these studies are carried out to answer the research questions as set out in section 1.3. Study 1 aims to understand ECs that are associated to requirements change, study 2 aims to understand the specification development process, and study 3 aims to understand the requirement formulation for a specification at the early stage of the design process.

Chapter 5: Prescriptive and descriptive study

This chapter describes the proposed design support to facilitate design engineers to decompose the design problem and formulate requirements in a specification. A preliminary evaluation process and evaluation results of the support are also described.

Chapter 6: Summary and future work

This chapter provides a summary of the research results together with the main conclusions. Some drawbacks of the research study are highlighted and a few recommendations for future research are discussed.

Appendices:

- Appendix A, 'Interview Questions,' contains a copy of questions used to investigate the specification development process and requirement changes during the design process in a consultancy company.
- Appendix B, 'The Design Support Booklet,' consists of a copy of a proposed technique to decompose the design problem and to formulate requirements in a specification.
- Appendix C, 'The Evaluation Form,' consists of a copy of questions used to evaluate the design support
- Appendix D, 'The Assignment,' consists of a copy of the design problem, market research and drawing.
- Appendix E, 'Sample Feedback Of Design Support,' provides an example of extracted transcripts from the feedback of the design support.

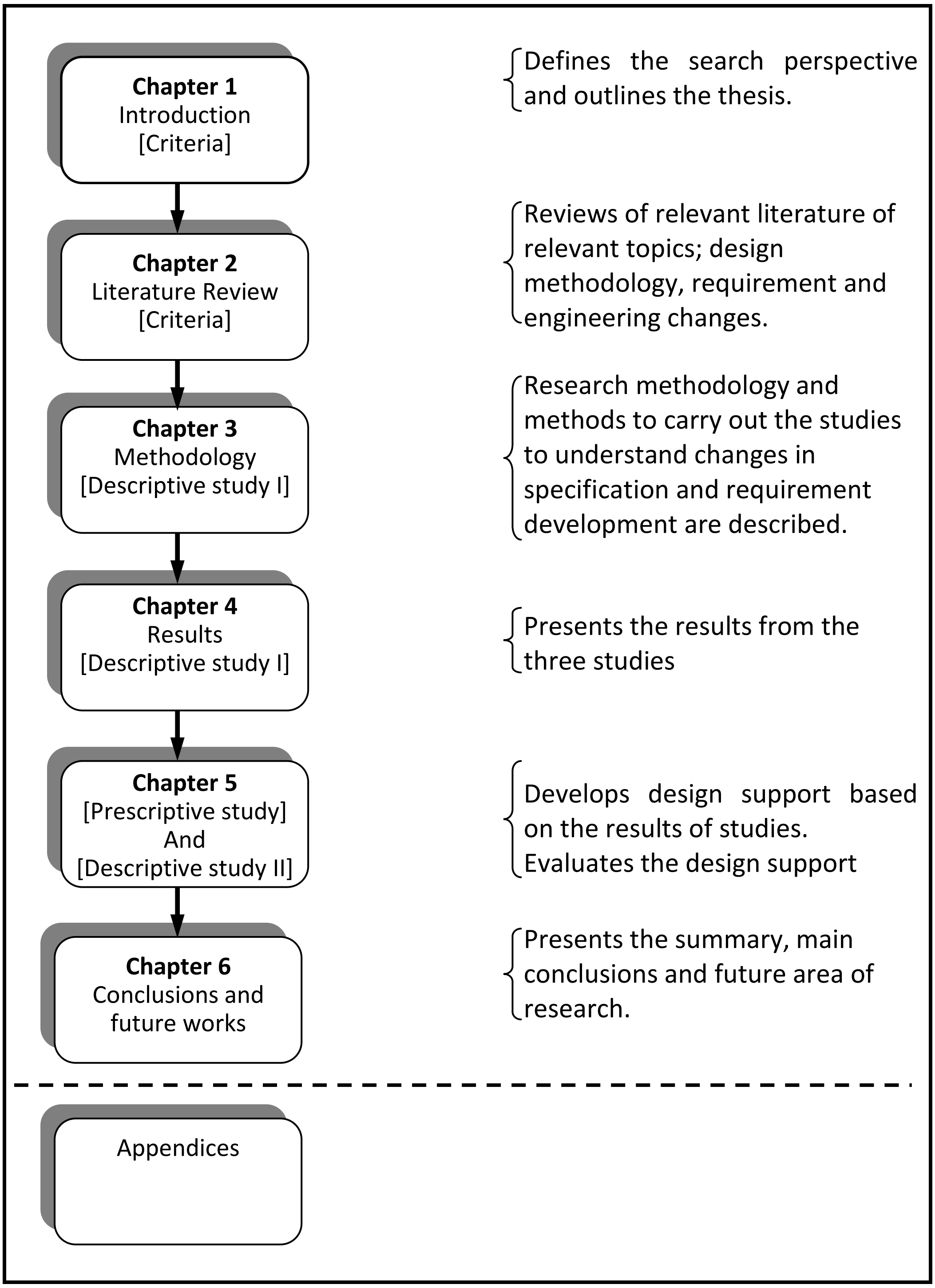


Figure 1.1 Outline of thesis

1.6 Terminology

Throughout this thesis, the term ‘‘requirements’’ refers to the written requirements in a specification. A specification is a document that contains requirements. However, the word ‘‘change in requirement’’ and ‘‘change in a specification’’ are referring to the same changes that are carried out to the written requirements (or full specification). In particular, in chapter 4 in study 1, this term is used to position the term used in the particular company. The ‘product’ refers to the final and tangible product. Thus, all ECs terms used in this thesis are referring to the change of the final product. ‘‘Flaw’’ is the characteristic of the product that does not meet the desired requirements. ‘‘Customers’’ refer to the stakeholders of the product. “Better specification” is also refers to “better requirements” that is specification that have fewer changes during the product development process. Additional terms have been defined as and when they are used throughout this thesis.

CHAPTER 2: LITERATURE REVIEW

This chapter presents a review of the literature in three areas, namely: 1) Engineering Design Methodology; 2) Design Specification; and 3) Engineering Changes. All these areas were reviewed due to their association to the research objects namely the specification and its constituents.

2.1 Engineering design methodology

The review of the design methodology aims to present an overview of the roles and significance of specification in the context of the product development process. This review examines the prescriptive models of the design process as prescribed in the design methodology literature and the descriptive models of the design process based on empirical studies. The commonalities and differences between these two models are highlighted and concluded.

Pahl and Beitz [1996] define design methodology as a concrete course of action for the design of technical systems that derives its knowledge from design science and cognitive psychology, and from practical experience in different domains. A design methodology must therefore:

- Encourage a problem-directed approach i.e. it must be applicable to every type of design activity regardless of the field of specialisation;
- Foster inventiveness and understanding i.e. facilitate the search for optimal solutions;
- Be compatible with concepts, methods and findings of other disciplines;
- Not rely on finding solutions by chance;
- Facilitate the application of known solutions to related tasks;
- Be compatible with electronic data processing;
- Be easily taught and learned; and
- Reflect the findings of cognitive psychology and modern ergonomics i.e. reduce workload, save time, prevent human error and help to maintain active interest [Pahl and Beitz 1996].

There are a number of well-known contemporary contributions in the field of design methodology. These include Pugh's methodology which encompasses the total design and development process [Pugh 1997], Cross' methodology which explains the systematic design process [Cross 2000], Andreasen and Hein's methodology which emphasises integration in terms of the creation of market, product and production [Andreasen and Hein 2000] and Pahl and Beitz's methodology which explains the systematic approach of the design process covering, phase, task and outcome of the particular phase. Additionally, there is Ulrich and Eppinger's methodology of the design process emphasising on the procedures and methods for major activities, particularly in the product planning and conceptual design phase [Ulrich and Eppinger 2004]. Last but not least, there is Ullman's methodology which focuses on the mechanical design process through a step-by-step process comprising design stages and generic design tasks with practical examples such as bicycles [Ullman 2003].

2.1.1 Models of the design process

The design process is a combination of the physical and cognitive process. Two examples of prescriptive models are shown in Figure 2.1 and Figure 2.2. The prescriptive design process models [Pahl and Beitz 1996; Pugh 1997, Hubka and Eder 1988] have converged to form what is called the consensus model as it is prescribed as a systematic process, and have been divided into four conceptual phases: 1) task clarification; 2) conceptual design; 3) embodiment design; and 4) detail design phase [Roozenburg and Cross 1991]. According to Blessing [1996], the development of prescriptive models and methods resulted due to disagreements regarding the practice in which the design process was carried out. Thus, as Blessing [1996] noted, the purposes of the design methodologies were to:

- Try to rationalise creative work;
- Reduce the probability of forgetting something important;
- Permit designs to be taught and transferred;
- Enable computer support;
- Facilitate planning of the design process;
- Allow control of the process from the point of view of both efficiency and effectiveness; and

- Improve communication between disciplines involved in design through a common set of concepts.

Blessing [1996] distinguished the *prescriptive model* of the design process in terms of transformation from the problem in product description and classified this model into two groups: 1) *problem-oriented model* and 2) *product-oriented model*. The *product-oriented model* focuses on analysing the initial idea. Later on, this idea is transformed into a concrete concept by way of a stepwise refinement process whereas in the *problem-oriented model*, the abstract problem is transformed into a concrete concept through stepwise concretisation involving functions, physical principles and working principles. Although these two models differ substantially, they do share one similarity: a stepwise top-down, iterative approach to enable the monitoring of the design process and emphasise an understanding of the problem before developing solutions.

Furthermore, Blessing [1996] compares the prescriptive models with the descriptive models based on three themes: 1) the stage or phase; 2) the activity; and 3) the strategy of the models. A 'stage' is defined as a subdivision of the design process based on the state of the product under development; a 'design activity' is defined as a subdivision of the design process related to the individual problem-solving process; and 'a strategy' is defined as the sequence in which the design stages and activities are planned or executed. The study found that a large overlap occurred between these models at the problem definition stage, and the approach in practice was less structured and systematic. In addition, Blessing found that the *problem-oriented model* was rarely observed in practice.

However, the importance of problem definition as stressed in the prescriptive literature has been supported by several descriptive studies [Cooper 1990; Ehrlenspiel and Dylla 1991, cited in Blessing 1996].

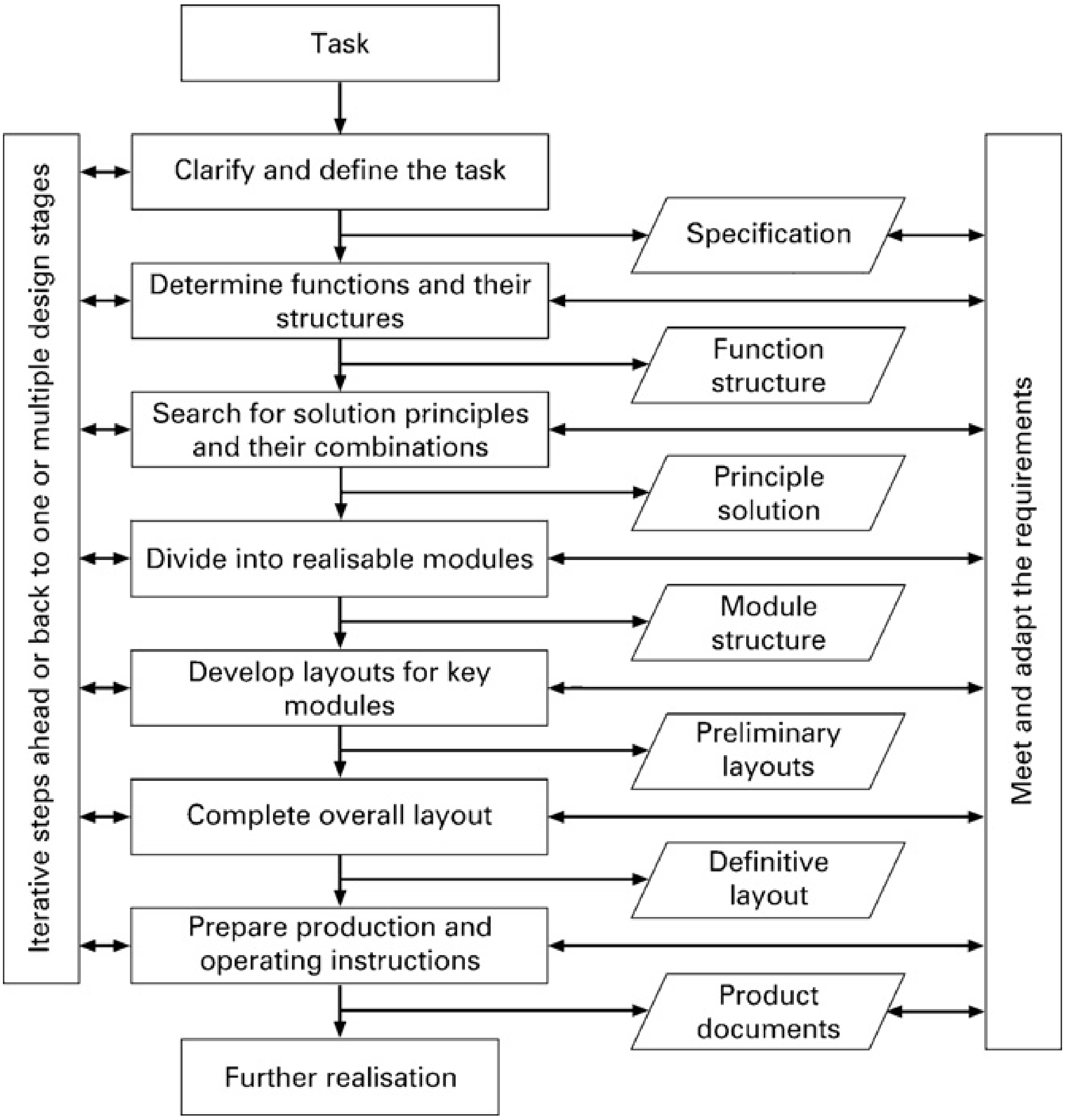


Figure 2.1 The VDI 2221 model of the design process [VDI 1993]

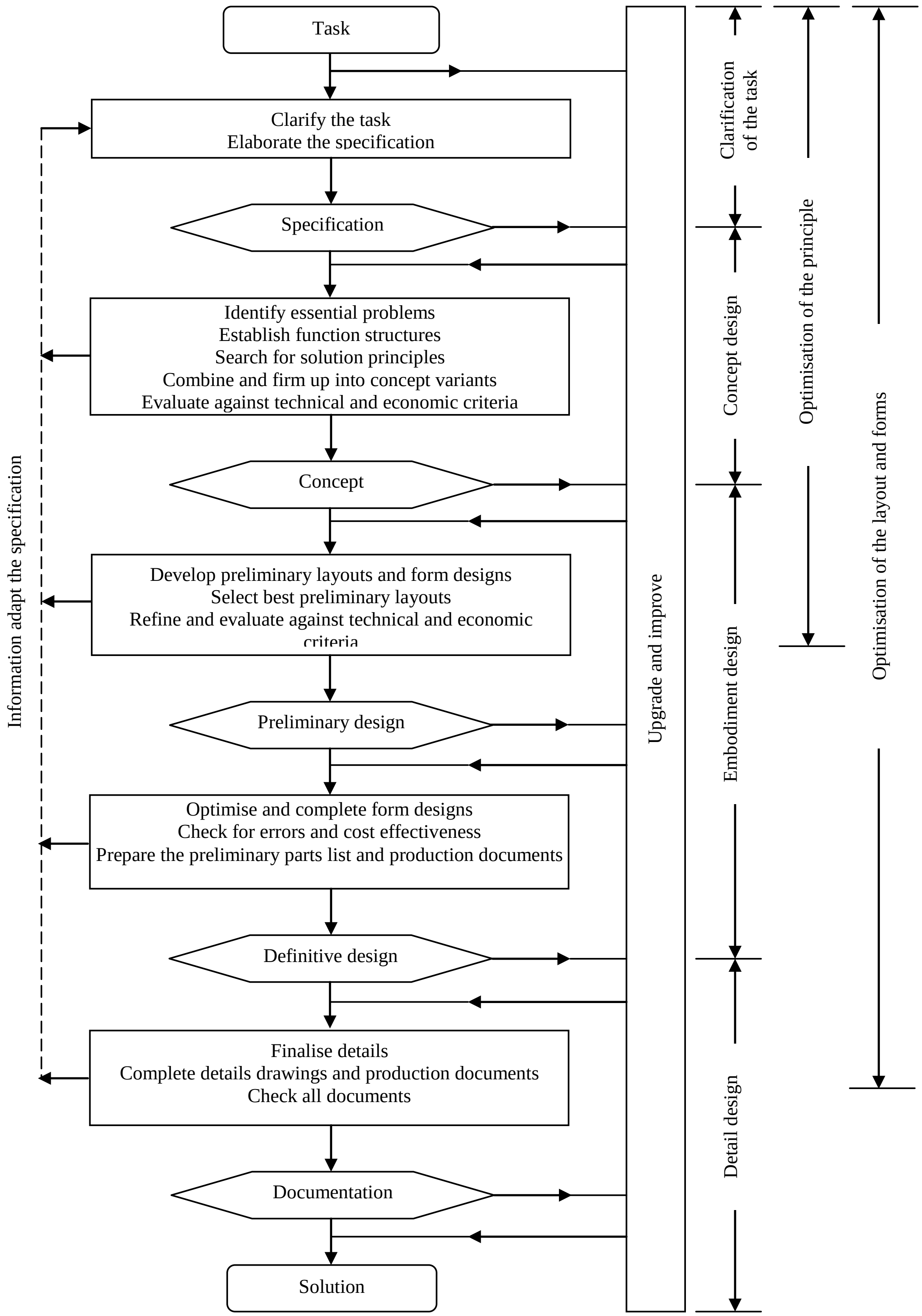


Figure 2.2 Steps of the planning and design process from Pahl and Beitz [1996]

In a separate study, Roozenburg and Cross [1991] compared the consensus design process models in the engineering design domain including Pahl and Beitz's model and Pugh's model with the architectural/industrial design domain. They found that the engineering design models emphasised the sequence of stages through which the project is expected to progress whereas the architectural/industrial design models emphasised the cycle of cognitive processes that the designer is required to perform. They concluded that the engineering models are more prescriptive while the architectural/industrial design models are more descriptive in nature.

Descriptive models for the design process usually identify the significance of generating solution concepts early on in the design process, thus reflecting the *solution-focused* nature of design thinking. This initial solution conjecture is then subjected to analysis, evaluation, evaluation and refinement [Cross 2000]. In addition, Cross [2000] developed a design process model consisting of four essential design activities: 1) exploration; 2) generation; 3) evaluation; and 4) communication as shown in Figure 2.3, along with a generic model for creative problem-solving.

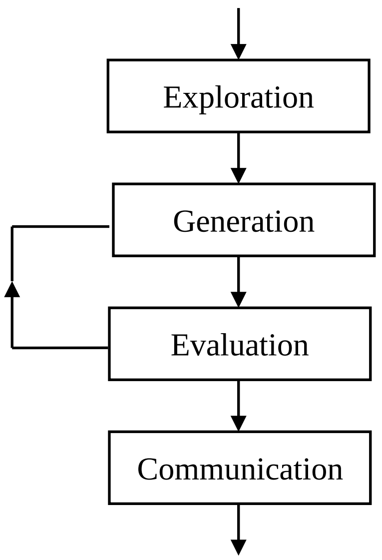


Figure 2.3 Cross' four-stage model for the design process

To represent an engineering design process, Gero [1990] proposed a Function-Behaviour-Structural model of design (FBS model) as shown in Figure 2.4. The model consists of eight fundamental processes:

- Formulation (process 1) transforms the design requirements expressed in function (F) into behaviour (Be) that is expected to enable this function.
- Synthesis (process 2) transforms the expected behaviour (Be) into a solution structure (S) that is intended to exhibit this desired behaviour.
- Analysis (process 3) derives the actual behaviour (Bs) from the synthesized structure (S).
- Evaluation (process 4) compares the behaviour derived from structure (Bs) with the expected behaviour to prepare the decision if the design solution is to be acceptable.
- Documentation (process 5) produces the design description (D) for constructing or manufacturing the product.
- Structural reformulation (process 6) addresses changes in the design state spaces in terms of structure variables or ranges of value for them if the actual behaviour is evaluated to be unsatisfactory.
- Behavioural reformulation (process 7) addresses changes in the design state spaces in terms of behaviour variables or ranges of value for them if the actual behaviour is evaluated to be unsatisfactory**.**
- Functional reformulation (process 8) addresses changes in the design state spaces in terms of functional variables or ranges of value for them if the actual behaviour is evaluated to be unsatisfactory.

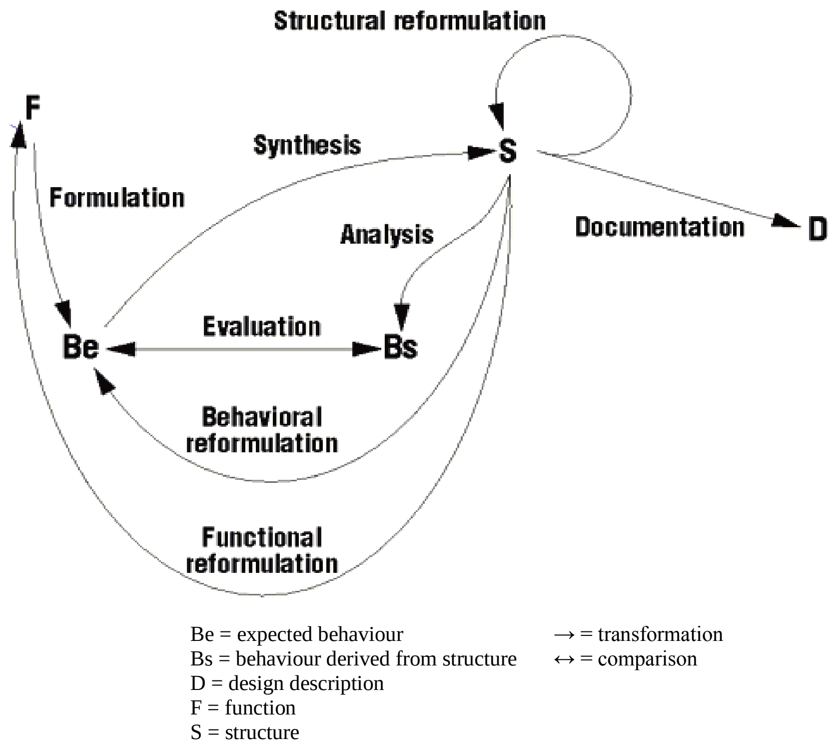


Figure 2.4 The FBS framework after [Gero 1990]

However, Vermaas and Dorst [2007] criticise Gero's FBS model due to its double status as a descriptive model that aims to capture how a designer actually designs and a prescriptive model that aims to improve designing by providing computer tools to assist designers.

Howard *et al.* [2008] extended Gero's model by proposing a *creative design process model* as shown in Figure 2.5. This model was developed based on an integration of both views: the design process in engineering design and the creative process in cognitive psychology.

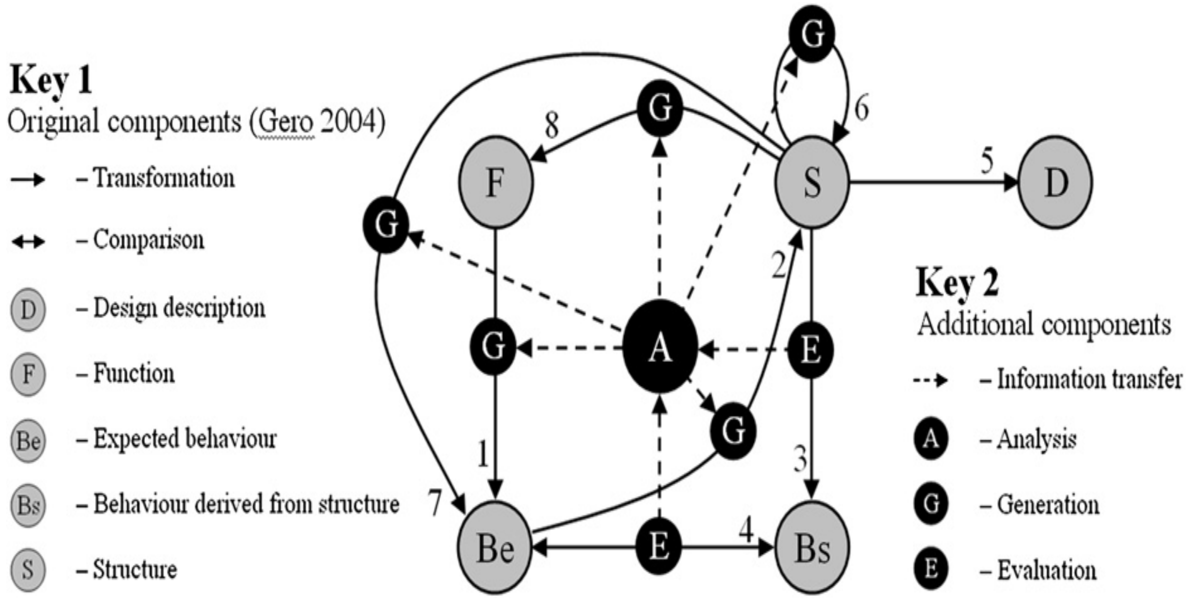


Figure 2.5 Integrated creative design process model [Howard et al. 2008]

Furthermore, Kurukawa [2004] developed a descriptive model for the cognitive design problem-solving process to illustrate designing as a problem-solving process as shown in Figure 2.6. This model describes a scenario-driven conceptual design information model. The model was developed based on the designer's cognition process observed in four design meetings undertaken by a company. The model consists of information elements generated through the cognitive design problem-solving process which Kurukawa argues is a basic design process.

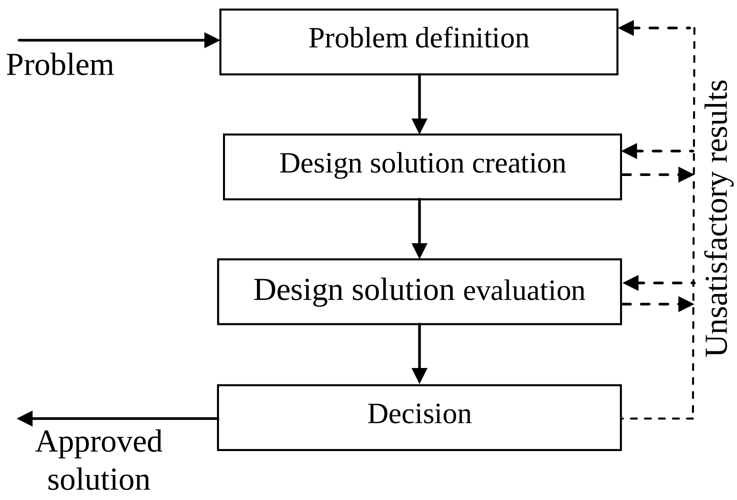


Figure 2.6 Cognitive design problem-solving processes from Kurukawa [2004]

To illustrate the design process as a chain of cognitive design problem-solving processes, a new model was developed as shown in Figure 2.7. This model is actually an extended version of the model in Figure 2.6. This model shows that design solutions are generated through cognitive design problem-solving processes and gradually become more concrete as the design process progresses.

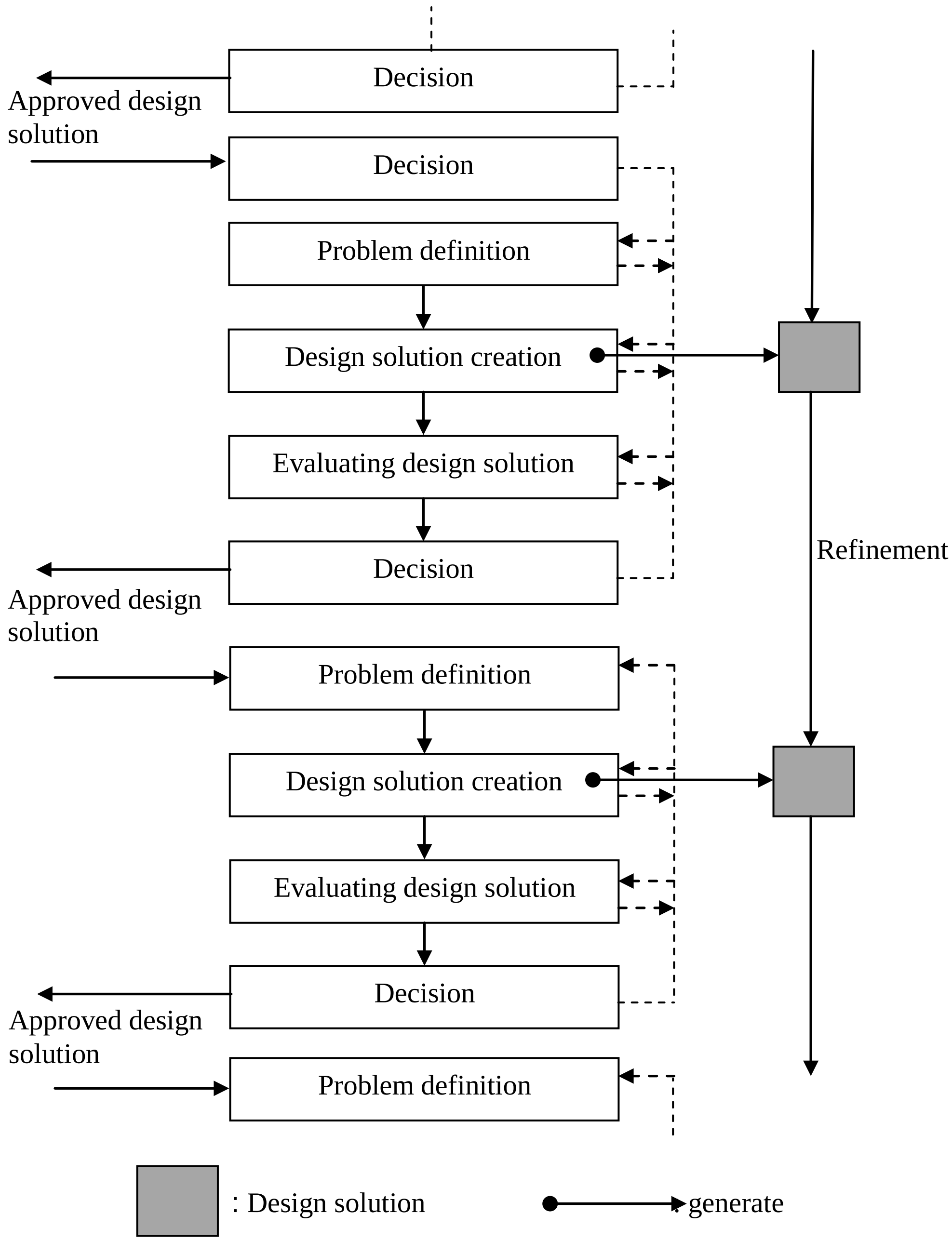


Figure 2.7 Design solution refinements from Kurakawa [2004]

In the problem domain, designers develop requirements and functions from the design objective so that the level of abstraction decreases step by step. See Figure 2.8.

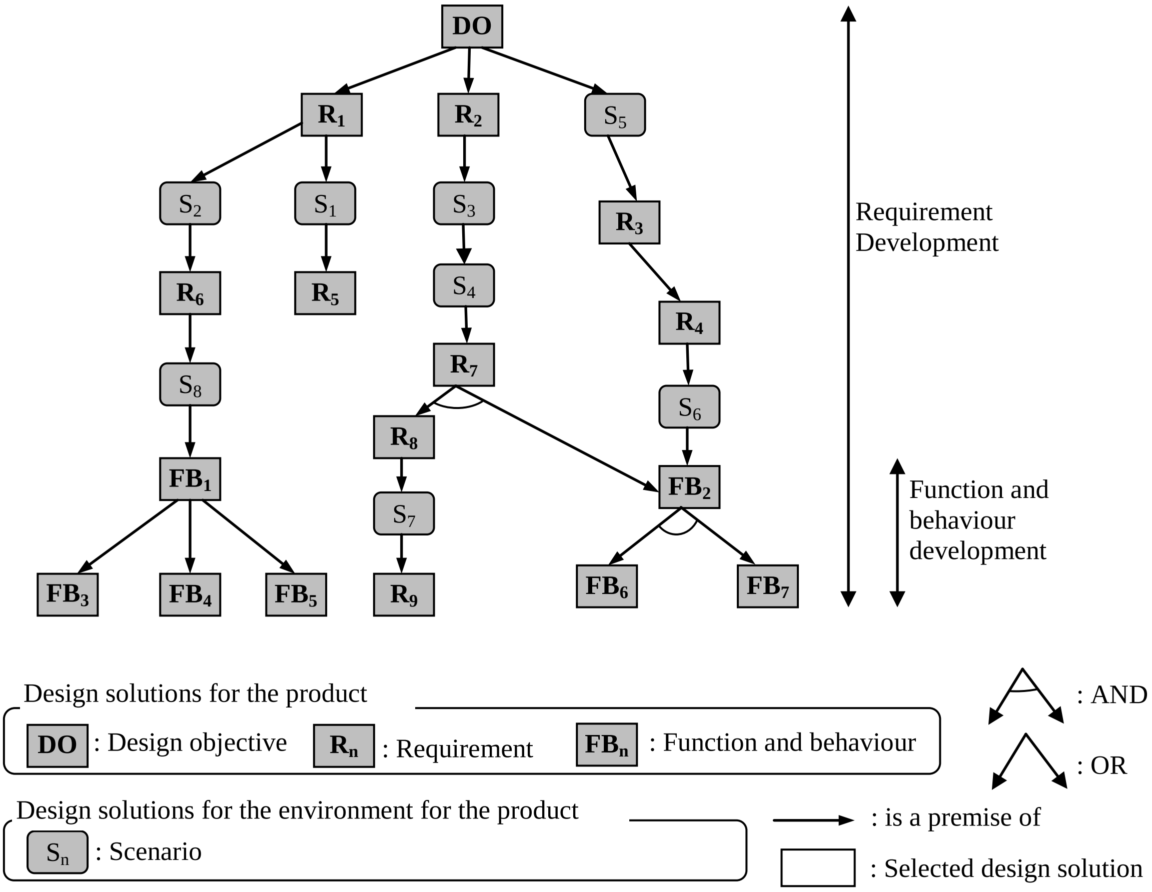


Figure 2.8 The requirement analysis/function decomposition phase from Kurakawa [2004]

The process of developing requirements and functions is repeated until the designers are satisfied with the results. In the iteration process, designers improve the requirements and functions they have already determined and consider the relationships between them. If they want to improve a certain requirement or function, they will generally need to change all sub-requirements and sub-functions of the product. This causes drastic design changes. However, if designers need to change only the wording of certain requirements or functions in order to improve them, they can do that in the way shown in Figure 2.9.

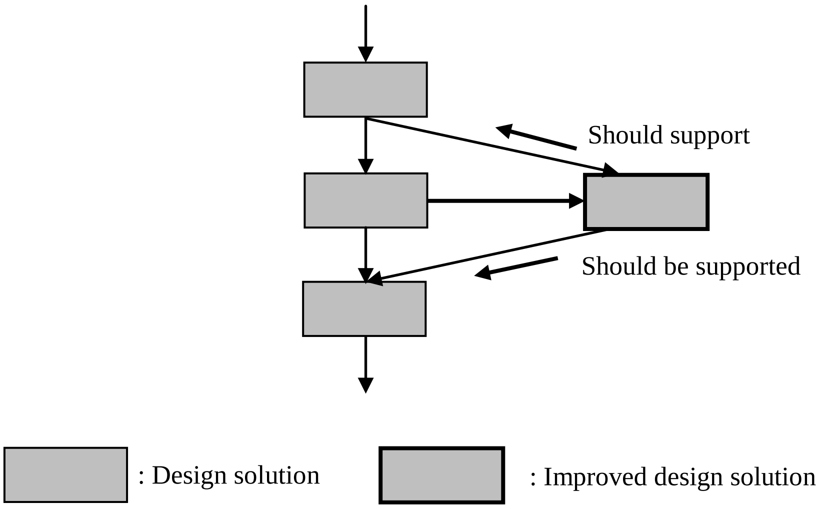


Figure 2.9 Improvement of the design solution form Kurakawa [2004]

According to Hybs and Gero [1992] the formulation of functional requirements is to define expected behaviour, B_e, which is represented as the problem space. The solution space can be considered to contain structure elements where the design process is to search the right combination of structure elements to satisfy the requirements, B_e. The behaviour exhibited by the current structural combination (B_s) is compared against B_e in evaluation process. Reformulation, which is defined as $S \rightarrow B_e$, is conducted if necessary. In addition, Maher and Poon [1996] proposed a model of the design problem-design exploration as co-evolution. Figure 2.10 illustrates the problem-design exploration as the interaction between problem-space (the required behaviour) and solution-space (the potential structure combinations). This model highlights the co-evolution of the behaviour space with the solution space over time and has the following characteristics:

- There are two distinct spaces: behaviour space and structure space.
- These state spaces interact over a time spectrum.
- Horizontal movement is an evolutionary process.
- Diagonal movement is a search process where goals lead to solutions. This can be:
  - Downward arrow: '*Problem leads to solution*' or *synthesis* where $B_e \rightarrow S(B_s)$. The behaviour-space (t) is the design goal (the required behaviour) at time *t* and structure space (t) is the solution space which defines the current search space for design solution.

– Upward arrow: '*Solution refocuses the problem*' or *reformulation* where $S \rightarrow B_e$. The structure-space (t) becomes the goal and the selection force to evaluate individuals in the behaviour space at time t+1.

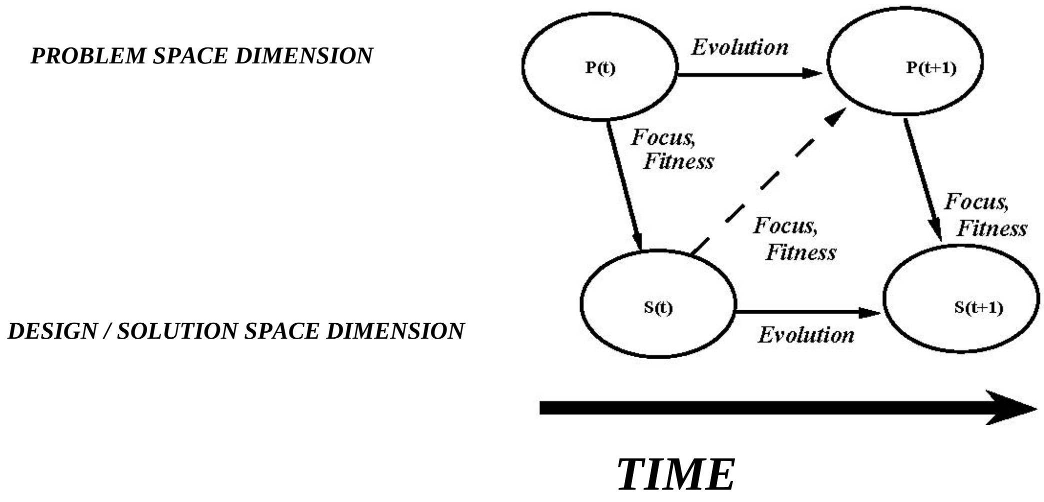


Figure 2.10 Co-evolution of problem-space and design solution-space [Maher and Poon 1996]

Jin and Chusilp [2005] proposed a cognitive activity model of conceptual design based on four key cognitive activities, namely analyse problem, generate, compose, and evaluate as shown in Figure 2.11.

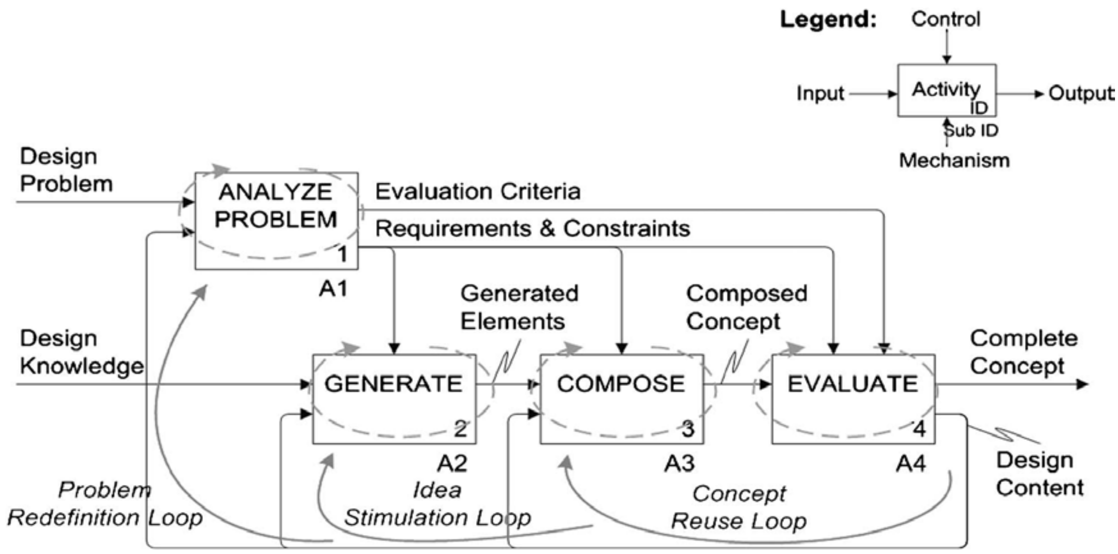


Figure 2.11 A cognitive activity model of conceptual design [Jin and Chusilp 2005]

Despite the abundance of prescriptive design models in the design methodology literature, these models are generally not accepted in practice. The reasons for this circumstance have been reported by several researchers [Maffin 1998; Frost 1999; Nieberding *et al.* 2007; Tomiyama *et al.* 2009]. Among others, Nieberding *et al.* [2007] highlight that: 1) the prescriptive models and methods are based on the "original design problem" while most industrial design problems are adaptive or variant designs; and 2) the prescriptive models and methods are not flexible enough to take the constraint and context of a development life cycle into account. However, according to Frost [1999], the prescriptive models are accepted in practice when subjected to adjustments to fit into the context of a particular organisation and project. Meanwhile, Maffin [1998] argues that what is truly needed is a model for interpretation of the design process rather than a model for prescription.

2.1.2 Empirical study of the design process

In practice, the design process is not linear in the sense that the problem is completely defined at the beginning and the design solution is directly derived from it. Thus, several studies have been conducted by industries and laboratories to understand the design process. To comprehend how the design process is executed at the organisation level, Löfqvist [2009] carried out a multiple case study of three small established companies in Sweden. The results showed that the design processes differ even within the same company. The results also showed that relative novelty affects the design process, i.e. the novelty of the product to be developed was low, a linear, structured and systematic design process was found to work. A design process that was cyclical, experimental and knowledge-creating seemed to work irrespective of the product's novelty.

Dorst and Dijkhuis [1995] compared two paradigms of design activities in order to describe the industrial design process. Their study aimed to identify how close these paradigms were to the design activities as experienced by designers themselves. These paradigms were: 1) design as a rational *problem-solving process*; and 2) design as a *process of reflection-in-action*. The *problem-solving* approach defines design as a search process in which the scope of the steps taken towards a solution is limited by the information-processing capacity of the acting subject. The problem definition is ideally stable and defines the ‘solution space’ that has to be surveyed. In contrast, the reflection-in-action approach is defined as design as a reflective conversation with the situation where problems are actively set or ‘framed’ by designers who take action (make ‘moves’) to improve the (perceived) current situation. To conclude, they describe design as a rational problem-solving process, particularly in situations where the problem is fairly precise and the designer has strategies that he/she can follow to solve them. Describing design as a process of reflection-in-action works particularly well in the conceptual stage of the design process, where the designer has no standard strategies to follow and is instead proposing and trying out different problem/solution structures.

Kruger and Cross [2006] analysed the data from a protocol study of nine experienced industrial designers in a laboratory setting to perform the same design task. This study aimed to draw an expert model of the design process. The task was to create a concept design for a litter system. As a result, they identified four *cognitive strategies* of design tasks and categorised them as follows:

- *Problem driven design*: the designer focuses closely on the problem at hand and only uses information and knowledge that is strictly needed to solve the problem. The emphasis lies on defining the problem and finding a solution as soon as possible.
- *Solution driven design*: the designer focuses on generating solutions and only gathers information that is needed to further develop a solution. The emphasis lies on generating solutions. Little time is spent on defining the problem, which may be reframed to suit an emerging solution.
- *Information driven design*: the designer focuses on gathering information from external sources and develops a solution on the basis of this information.
- *Knowledge driven design*: the designer focuses on using prior, structured, personal knowledge and develops a solution on the basis of this knowledge. Only minimal necessary information from external sources is gathered.

Furthermore, they found that for almost all designers, the most frequent activities were gathering data, identifying constraints and requirements and generating partial solutions. In general, they found that sequencing of activities and the iteration process occurred during the design process. These iterations were mainly observed within the analysis stage, with many iterations occurring between data gathering and identification of requirements. There was also a secondary iteration loop in the synthesis evaluation stage. Both the problem driven and the solution driven strategies used less iteration than the variants of information driven and knowledge driven strategies.

Fricker [1999] studied the characteristics of individual designers dealing with different types of problems, precise and imprecise. They found that the completeness of design problems affect the design approaches and subsequently the quality of the results. Smith and Tjandra [1998] focused their study on understanding iteration in the design process. This study was carried out in an experimental laboratory setting. However these studies provide an understanding of the design process at the individual level but not at the organisational level.

2.1.3 Conclusions

Prescriptive models of the design process have reached the consensus that there are four common stages in the design process: task classification, conceptual design, embodiment design and detail design. These models are mostly developed based on the knowledge and personal experiences of individuals in the industry [Blessing 1996].

Descriptive models of the design process generally focus on the conceptual design stage and are developed based on the cognitive psychology of design engineers in carrying out the design tasks. The majority of research with regard to the design process focuses on the design activities and strategies of individual design engineers within a controlled experimental environment. These models are appropriate for understanding cognition and creativity in the design process of individual design engineers, but are not sufficient to understand design in an organisation setting. Thus, prescriptive models could be devised to support design at the individual level. Yet, there are descriptive models developed based on the design practice i.e. C-QUARK [Ahmed 2000].

Prescriptive models portray the ideal condition of the design process while the descriptive models portray the practice of the design process. Researchers attempt to devise a prescriptive model based on the design practice. The prescriptive model aims to increase the efficiency and effectiveness of the design process. Therefore, research aimed at understanding design in practice at the individual or organisation level is essential to devise design support that matches industrial needs.

2.2 Design specification

To gain a more thorough background of design specification in the product development context, a review of design specification was carried out in more detail. This review provides a foundation to study specification in greater detail in terms of defining its significance in the product development context. In conclusion, the subject of interest to be researched in respect to design specification is highlighted.

2.2.1 Design specification in general

‘Specification’ is defined in several ways by different authors in the design literature. Some define specification based on its purposes. For instance, Ulrich and Eppinger [2000] define specification as a precise description of what the product has to do. Roozenburg and Eekels [1995] define specification as the elaboration of the goal of a product development project that has to be expressed in more statements or a list of objectives that has to be met and therefore, it usually contains different types of objectives which play a different role in the evaluation and selection of proposals. They decompose objectives into non-scaling and scaling. A non-scaling objective can be either a requirement or a wish whereas a scaling objective is only for a wish. In addition, requirement is divided further into product-specific objectives and standards. On the other hand, Darlington and Culley [2002] define design specification as a description of the desired solution to a problem. In addition, [Pahl and Beitz 1996] state that “the purpose of this clarification of the task is to collect information about the requirements that have to be fulfilled by the product, and also about the existing constraints and their importance. This activity leads to the formulation of a requirements list”. The requirement list is the same as design specification – a document that is continually reviewed.

Specification is also defined based on its content. To illustrate, Hansen and Andreasen [2007] use the term ‘product design specification’ for a specification document that contains a set of specification statements. They state that a specification statement can be formulated as a fixed requirement, a minimum requirement, a demand, a criterion or a wish. Meanwhile, Hubka and Eder [1988] define design specification as a list of properties of a technical system that do not exist at that time. Several other authors define specification as a written document for example Smith and Reinartsen [1991], who describe it as a written description of products that are generated in advance to guide the product development process. Pugh [1997] defines product design specification (PDS) as a control document that represents the specification of what is trying to be achieved– not of the achievement itself.

Dieter [1991] defines specification as "a detailed document that describes what the design must be, in terms of performance requirements ... but it should say as little as possible about how the requirements are met. Whenever possible the specification should be in quantitative terms, and when appropriate it should give limits within acceptable performance lies". Kohoutek [1996] defines specification as a document that prescribes, in a complete, precise and verifiable manner, the requirements, constraints, expected behaviour or other characteristics of a product or system. Another new is that of Elliot [1993] who argues that it is necessary to identify who should be involved; who should provide the information and in what form it should be presented in defining requirements in the early part of the design process. Elliot also comments on the role and nature of specifications: "... to turn the abstract and (usually) ill-formed idea of the customer (his/her dream) into a concrete statement of requirements against which the supplier can tender and carry out a detailed design".

From another point of view, the design specification is regarded as a model reproducing the problem and the criteria for the product to be designed. Its purpose is to specify product properties concerning manufacturing, marketing, usage and destruction but may also be used for evaluating properties like expected costs and time consumption of the design project [Buur and Andreasen 1989]. According to Cross [2000], "a specification defines the required performance and not the required product". In addition, Andreasen [2010] divides specification into two categories: 1) *target specification*; and 2) *result specification*. Target specification defines the target to be met by the product being designed while result specification is the detail drawing of a product before production.

Malmqvist and Schachinger [1997] developed a formal data model for design specification information and described the data items of the specification. The design specification consists of:

- Metadata: A standard set of attributes such as identity, product and subsystem name, description, version, status etc. is needed to administratively keep track of the specification.
- Requirement: The design specification is decomposed into a set of requirements.
- Referenced documents: The design specification may further refer to a set of documents of various kinds such as old designs, customer surveys, laws and regulations.

Furthermore, they derived a model of entity relationship between a specification and a requirement as depicted in Figure 2.12. Many views of specification have been found in the literature. The requirement in a specification is discussed in the next sections.

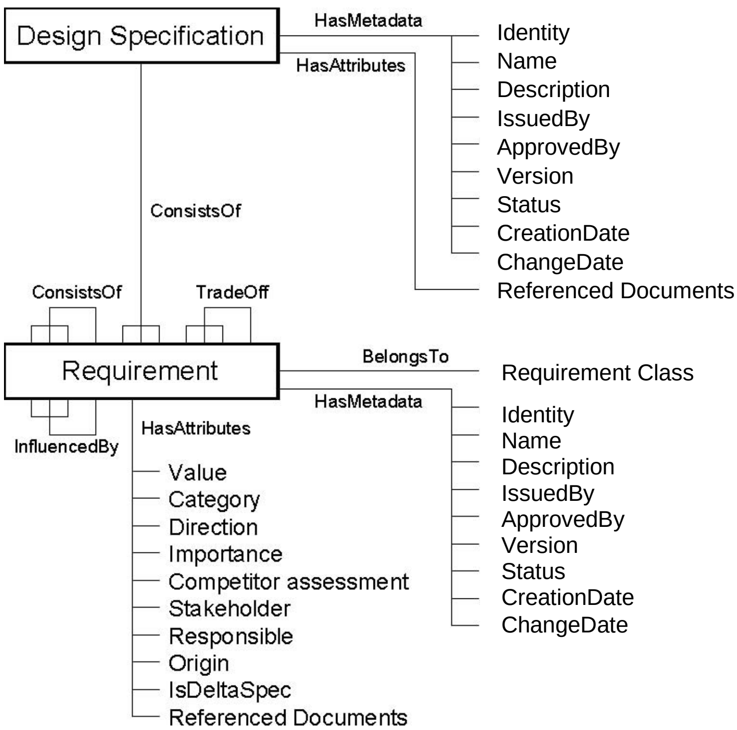


Figure 2.12 Entity-Relationship diagrams for design specification [Malmqvist and Schachinger 1997]

2.2.2 Requirements in a design specification

The terms ‘requirement’ and ‘specification’ are interchangeable and used by different authors to refer to the same things. Several authors have attempted to differentiate the two by defining ‘requirement’ as a statement and ‘specification’ as an artefact. Therefore, a ‘specification’ consists of a list of requirement statements while a ‘requirement’ has several meanings. Rios *et al.* [2006] defines a requirement as a single, unique and unambiguous statement in natural language of a single ‘what’ (non-functional) or ‘function’ that some class of user, stakeholder or client wants, followed by its attributes as they write; they should be written in a way that can be ranked, validated, traced, measured and verified. Eder [2008] defines a ‘requirement’ as a condition or constraint on a transformation process or technical system in its ‘as should be’ state. Furthermore, Eder states that a ‘condition’ is a thing or statement that must be fulfilled if another thing or statement is to be fulfilled. A ‘constraint’ is a thing or statement restricting or forcibly preventing another thing or statement. Ulrich and Eppinger [2000] describe a ‘specification’ as consisting of a metric and a value.

The design and requirements are coupled in practice as the intended properties of the design are stated as a requirement list. An individual requirement usually carries a single property of a design. Malmqvist and Schachinger [1997] describe an individual requirement with the following attributes:

- Metadata: A standard set of attributes such as identity, product and subsystem name, description, version, status etc. is needed to administratively keep track of the specification.
- Value: Each requirement will have its value, unit and tolerances specified.
- Requirement class: Examples of requirement classes include performance and geometry.
- Category: Requirement can be classified as demands (which can be sub-classified into functional requirements and constraints), wishes (or objective), options or information.
- Direction: The direction attribute of a wish category requirement provides further guidance for its value. For instance, it may be desirable to minimise or maximise the value of the requirement or to hit a specified target value. This

attribute may also refer to a value function that specifies a rating scale for the attribute.

- Importance: The importance of the attribute may be ranked on a scale.
- Competition assessment: This attribute keeps track of the competition as a list of brands with associated values for the requirement.
- Stakeholder: The stakeholder is the entity who requires the requirement, for instance the customer or the government.
- Responsible: The person who is responsible for the satisfaction of the requirement.
- Origin: The origin of the requirement is documented as original, derived due to a design decision, compensating or interfacing.
- IsDeltaSpec: This attribute marks a requirement that has changed since the last model of the product. This is useful in redesign situations.
- Descriptive document: May also be attached to the requirement.

A requirement in a specification belongs to the problem domain because it defines the design problem. Thus, the statement in a specification is considered a requirement if it describes a problem. A problem is characterised by three components:

- An undesirable initial state i.e. a satisfactory situation exists.
- A desirable goal state i.e. realising a satisfactory situation.
- Obstacles that prevent a transformation from the undesirable initial state to the desirable goal state at a particular point in time [Pahl and Beitz 1996].

Requirements are part of the design problem. According to Olsson [1976] in Hansen and Andreasen [2007], there are four elements to be considered when formulating a problem situation. Firstly, there is a *process*, e.g. a transformation, an action, an activity or a task. Here, the design team can ask: What is the process? What does the user want to do? Why? When? Secondly, there is a *result*, e.g. a product or a solution to be synthesised by the design team. Thirdly, the design team has to consider *the surroundings* in which the solution will be applied or operated. The fourth is *human being*, who are exposed or exposing the product as it is used.

2.2.3 Classification of requirements

For easier understanding, scientists or engineers prefer to classify all complex entities into smaller and more manageable categories. A classification of requirements helps to guide design engineers in compiling, organising and analysing product design issues [Round and Cooper 2002]. Andreasen and Hein [2000] use the term 'design specification' and classify it into seven categories:

- The problem specification which comprises the objectives of the task, its limits, activities and so on.
- The functional specification i.e. the sub-functions of the product and the conditions for this sub-function.
- The construction specification i.e. the relationship of the product with the system which it is to be a part of, and the division of the product into its known subsystems, if any. This includes the use of agreed components or principles, if any.
- The situation in which the product will be used i.e. a description of the product's use, input/output, operation or man/machine relations.
- The quality specification i.e. a definition of external properties, the company's level of quality requirements and so on.
- The sales specification i.e. a definition of the sales philosophy behind the product, important sales arguments and features, sales related requirements such as packaging, preparing the product for delivery, information material, distribution, service and so on. In addition, there may be a question of variations, relationships with existing products and perhaps important competitors and the product's position in relation to them.
- The production specification i.e. the total volume of production, future annual production numbers, purchasing questions and perhaps already defined production conditions (process, assembly and quality control).

Ullman [2003] classifies requirements into: 1) functional performance requirement; 2) human factor requirement; 3) physical requirement; 4) reliability requirement; 5) life cycle concern requirement; 6) resource concern requirement; and 7) manufacturing requirement. Salonen *et al.* [2005] classify requirements into seven classes: 1) requirement related to feasibility; 2) technical requirement; 3) requirement related to size and appearance; 4) requirement for manufacturing and assembly; 5) requirement related to installation and use; 6) requirement for service; and 7) requirement related to life cycle.

Requirements are also classified based on their importance in the design process. A requirement is stated as either a demand or a wish. A demand is an objective that any design proposal must necessarily meet. Meanwhile, objectives that are not essential in this sense are called wishes. Demands and wishes play different roles in the evaluation of the design [Roozenburg and Eekels 1991]. Hansen and Andreasen [2004] also acknowledge the roles of demands and wishes during the product development process. They state that demands will differentiate between solutions and non-solutions whereas wishes will differentiate between good and bad solutions.

2.2.4 Elements and contents of the design specification

The most important element in a specification is requirements as they define the target to be met. To allow better requirement management, other elements are also crucial. Therefore, Andreasen and Hein [2000] suggest the elements of a specification document as the following:

- Requirement for a product i.e. the fixed and unavoidable requirements which must be applied to the solution.
- Criteria i.e. those properties or qualities which one tries to attain in the product, and which demonstrate that it is a good product. These criteria are to be used to separate the good solutions from the poor ones.
- Desirable features of the product i.e. features, details or properties of the product which contribute positively to the value of the product and which you do not directly want to expend any effort on
- Remarks in the form of open questions or comments which turn into requirements or criteria as the design process proceeds and greater insight into the problem is attained.

Furthermore, Andreasen and Hein suggest that the technical contents of requirement statements in a specification document should cover the following themes:

- The problem specification which comprises the objectives of the task, its limits, activities, etc.
- The functional specification i.e. the sub-functions of the product and the conditions for these sub-functions.
- The construction specification i.e. the relationship between the product and the system which it is to be a part of, and the division of the product.
- The situation in which the product will be used i.e. a description of the usage of the product, input/output, operation or man/machine relations.
- The quality specification i.e. a definition of external properties and the company's level of quality requirements, testing, product responsibility, consent requirements, etc.
- The sales specification i.e. a definition of the sales philosophy behind the product.
- The production specification i.e. the total volume of production.

Not all verbal requirements must be written in a specification document. The content and degree of detail in the product specification must be adjusted to suit the number of design degrees of freedom which one wishes to exploit, for instance, how radically new the solution is to be. Which properties should be specified? The main principle is that the product must possess properties which make it the best possible product at all stages of its lifetime.

2.2.5 Characteristics of a design specification

With regard to the characteristics of a specification, Roozenburg and Eekels [1995] state that "design requirement is an incomplete description of product goals and needs to be updated during the design processes". This statement is in agreement with Andersson's [2003] observation that "the completeness is a criterion that is basically unachievable". A study by Hansen and Andreasen [2007] also supports this statement as they found that engineering designers generate requirements during the design process and not only prior to it. To ensure the clarity of requirements in the specification, Pahl and Beitz

[1996] suggest that the requirements should be further classified into demands or wishes. Furthermore, they classify wishes into major, medium or minor importance, quantify them and define them in the clearest possible terms. Pahl and Beitz [1996] also recommend the idea of structuring the requirements list according to the sub-systems in the situation where the assemblies to be developed or improved are already determined such as in automotive development.

Based on an empirical study, Hansen and Andreasen [2007] found that ‘a productive product specification’ that supports the synthesis of a product idea is one that expresses value, important aspects of product context and articulate key functions. According to Hansen and Andreasen, a specification which contains a lot of requirement statements about product properties do not support design engineers or design team in exploring the solution space until the product idea is known.

2.2.6 Design specification in the product development process

Product development methods in the literature basically prescribe product development as a well-structured sequential process, starting with a requirement specification or design specification and ending with a product solution [Pahl and Beitz 1996; Ulrich and Eppinger 2000; Pugh 1997]. To start a product development process, the company developing a consumer product investigates a promising product idea based upon the current market situation and economic outlook. However, regardless of whether the product idea stems from a product planning process or a specific customer order, it is still essential to clarify the task in detail before production starts. This clarification is important in order to collect information about the requirements of the product and information about existing constraints and their importance. This activity leads to the formulation of the requirements list (design specification) that focuses on, and is referred to, during the design process. [Pahl and Beitz 1996]. The result of the planning phase is the specification, namely the design requirements that will be used as a basis for the conceptual design phase and subsequent phases. This document is dynamic [Pugh 1997] and has to be updated continuously along with the product development process [Pahl and Beitz 1996]. In this respect, the design requirement is used for two purposes: 1) to guide design engineers to search for feasible solutions within the design space; and 2) to evaluate the solutions of each phase in the design process. Solutions at different stages of the design process will be evaluated against the design specification. This evaluation is needed in order to determine whether the solutions fulfil the specification (requirements list) or not [Pugh 1997].

The establishment of design specifications in the early part of the design phase that is kept in focus all through the product development process has been proposed in the design methodology [Pugh 1997]. In the Functional-Behaviour-Structure (FBS) framework, Gero and Kannengiesser [2006] outline eight fundamental processes of designing. The framework prescribes design as starting with the formulation process. Formulation is an important process in conceptual design as it specifies the initial design state space i.e. the design specification for which the design solution is sought [Gero and Kannengiesser 2004]. Thus, a prescriptive method is required to help in finding, formulating and redefining the focus of design efforts for a specific situation [Nadler *et al.* 1989]. Specification has been found to be an important means to co-ordinate the work in the different groups and as a basis for development work [Blessing 1994].

2.2.7 Problems faced by designers with regard to the requirements statement

Empirical evidence of the problems faced by users of the specification with regard to the requirements statement is essential feedback for specification developers to respond to. To understand these problems, Karlsson *et al*. [1998] carried out a study survey with more than 300 suppliers to European automobile OEM (Original Equipment Manufacturer). Numerous problems were identified and categorised as follows: 1) technical content and the level of detail in requirements; 2) changes in specifications; 3) cost; 4) interpretation and understanding; and 5) supplier participation in the specification process.

In respect to technical content, the first problem found in the Karlsson's study was that specifications were sometimes very general or vague and did not cover the requirements of the specific part or product in question. The second problem was related to over specification. Many times, the correct tolerance level was not mentioned or very narrow tolerance was given. In some cases, the content (functional solution, material, and dimension) of a specification can be 'extreme' i.e. very hard or even impossible to realise with existing technology.

In a separate study, Karlsson and Åhlstrom [1996] observed a similar phenomenon in the study carried out in an international manufacturing firm producing mechanical and electronic office equipment. They found requests for detailed specifications were regularly observed in different projects. Specifications that contained fairly detailed descriptions of the product were requested whereas specifications about product functions were not formulated in detail enough.

In terms of changes, they found that there were too many changes in the specifications. These changes means rework and thus delays in the product development process. Changes can be due to a number of reasons such as mistakes, conflicts between demands within the OEM's different technical centres and the need for interaction in the functional system. Often the reason behind changes in specification are not mentioned to the suppliers, thus making it harder for them to adapt and optimise component characteristics and to understand the implications that the changes might bring in relation to the evolution of a system. In general, the specification that the supplier received from OEM was about 60% to 70% complete and still subjected to changes. The result of an empirical study found that the difficulties faced by design engineers during the task clarification led to the customer changing the requirements and as a result of the requirements being formulated too late [Romer *et al.* 2001].

2.2.8 Models of the design specification development process

General models of specification development

The formulation of any requirements in a specification is one of the crucial tasks at the start of project. Without well-defined requirements, design engineers have no definition of what they want to build. Customers also have no definition of what to expect and there is no reference to verify partial solutions. A requirement must be understood in enough detail to facilitate design synthesis. Requirements are reviewed to ensure that they are clear and that the development team has a full understanding of them. The significance of the specification development process and requirement formulation has been acknowledged by several authors in design literature. Specifications and the specification development process are critical in the overall product development process for controlling design engineers to achieve promising solutions [Nellore *et al.* 1999].

To ensure that the requirements are well-defined, several guidelines have been proposed to facilitate the formulation of requirements. Nellore *et al.* [1999] outline a few reminders on how to draw good specifications as follows:

- Ensure broad input into the overall specification, from the customer, distributor and supplier and feedback from previously verified requirements stemming from analysis of previous development projects.
- Create a customer specification. In parallel, create compliance cards (internal product specifications) setting internal innovative goals in order to create a positive value gap for customers.
- Ensure validation plans at each specification level.
- Identify priorities through risk and bottleneck analysis.
- Ensure feedback at all levels of the specification process and ensure all solutions and changes are recorded.

Roozenburg and Eekels [1995] also proposed a procedure for developing a design specification. The procedure comprises three phases: listing objectives, analysing objectives and editing objectives. In order to achieve a complete collection of objectives and to minimise the chances of missing relevant objectives, the use of a checklist was suggested. This checklist contains three major elements, namely the stakeholder, the *aspects* i.e. performance, environment, safety, etc. and the life cycle of the product.

Smith and Rhodes [1992] proposed sequential steps for generating a good and systematic specification as follows:

- Determine objectives, such as the extent of the search (location) and the benefits expected (areas to be identified in the competitive products);
- Search and locate the manufacturers and distributors of the competitive products;
- Obtain the information;
- Sort and collate the information;

- Synthesise and analyse with the help of tools and deduce;
- Apply the extraction of data from information areas relevant to each specification element and decide on the information to be incorporated in each specification element.

In addition, Smith and Rhodes also emphasised the need to understand and interpret market needs for specification development. Finally, they determined 32 primary elements that should be included in a specification.

Pugh's approach relies on a checklist of 32 issues (refer to Figure 2.13) that a specification developer has to consider in order to develop a product design specification (PDS). Whereas, in the theory of properties, Eder and Hubka [1988] stated that "a machine or mechanical product is defined by its basic properties: the structure of the whole product, the form, materials, dimensions, surface and tolerances of the individual elements". On the basis of these technical properties, Eder [2008] proposed a method to turn these properties into requirements.

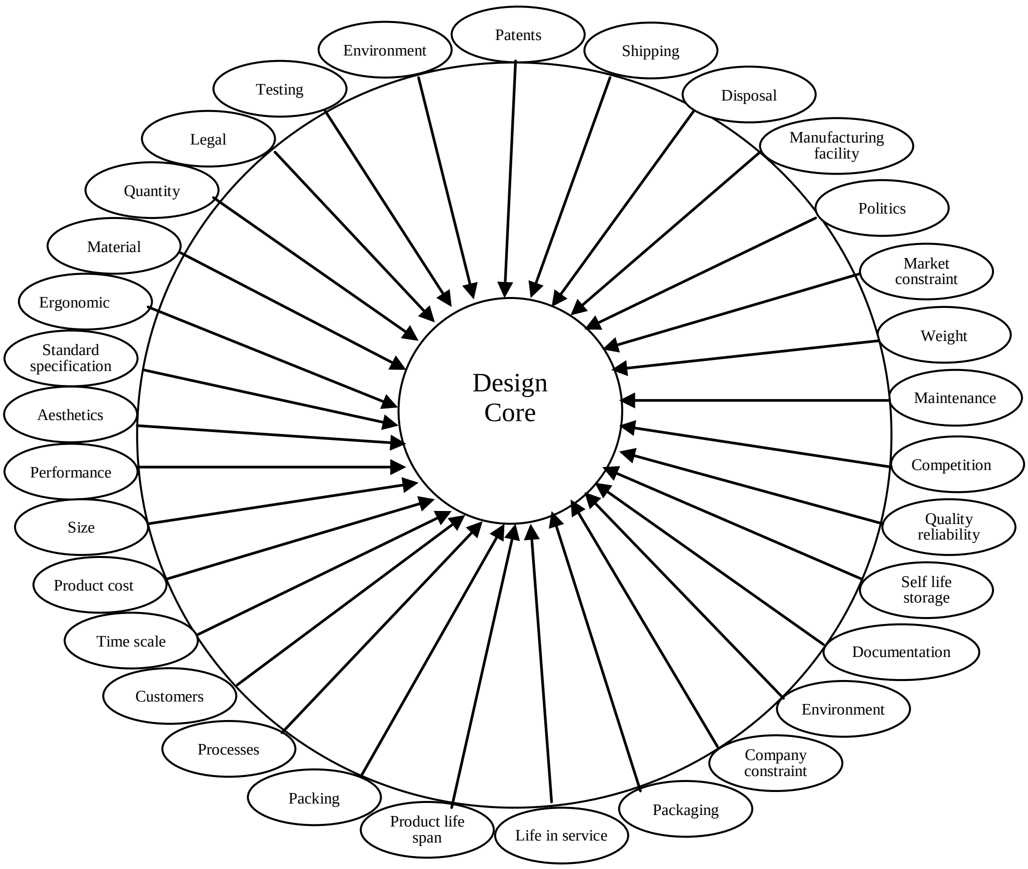


Figure 2.13 Elements of PDS from Pugh [1997]

With the aim to teach students how to write good specifications, Abe and Starr [2003] introduced an approach called design structured teardown processes. These processes were divided into six different phases with associated tasks and outcomes that contribute to the writing of specifications. In the course of the processes, they found that the specifications evolved in scope and became more detailed as the students worked through the phases, operating the product, dismantling it, measuring, drawing, computing and identifying materials, components and functions.

The development of requirement specifications is also done by accumulating knowledge about the desired system in a progressive manner. This process can be supported by an analysis-revision cycle in which the analysis phase checks the correctness of a given specification. The revision phase modifies it if problems are detected. To date, the analysis and revision activities have been typically considered in isolation, resulting in ineffective support for the design work. In response to this situation, Garcia-Duque *et al.* [2009] introduced methodologies to evolve formal specifications through two basic types of evolutions (refinement and retrenchment) in an analysis-revision cycle.

To formalise customers' requirements, Brace and Thramboulidis [2010] proposed a systematic approach to refine and extend requirements that are usually expressed by the customer in a narrative format into concrete specifications. This approach aims to digitise the formalisation of requirements instead of a document-centric method which is a labour intensive process. Hosnedl *et al.* [2010] devised a computer-based tool to support the development of product design specification and its evaluation. This innovated software was developed in the MS Excel platform based on the theory of technical systems.

During the product planning procedure of a machine tool, experienced or senior designers consider various kinds of customer requirements while simultaneously conducting the necessary information processing so as to finally determine the most suitable product specifications. With the aim of systematising this procedure, Perez *et al.* [2006] thus focused on the basic essentials to deal correctly with functional requirements and geometric tolerance at the specification stage of the design process. This was done to guarantee subsequent computer-aided tolerance synthesis at the basic and detailed design stages. They subsequently developed an experience-based method and applied it to a set of real cases. The obtained results show that the objectives proposed in this work were reached. Darlington and Culley [2004] developed a model of factors influencing design requirement development as shown in Figure 2.14. The model is arranged to reflect the central role played by the design company in determining which factors affect design requirement development in a given situation and the extent of their influence. This model can be used to characterise a company in respect of the specific factors which influence its own design requirement capture process. It may also be used to assess improved strategies for developing the design requirement in a manner more appropriate to the company in question.

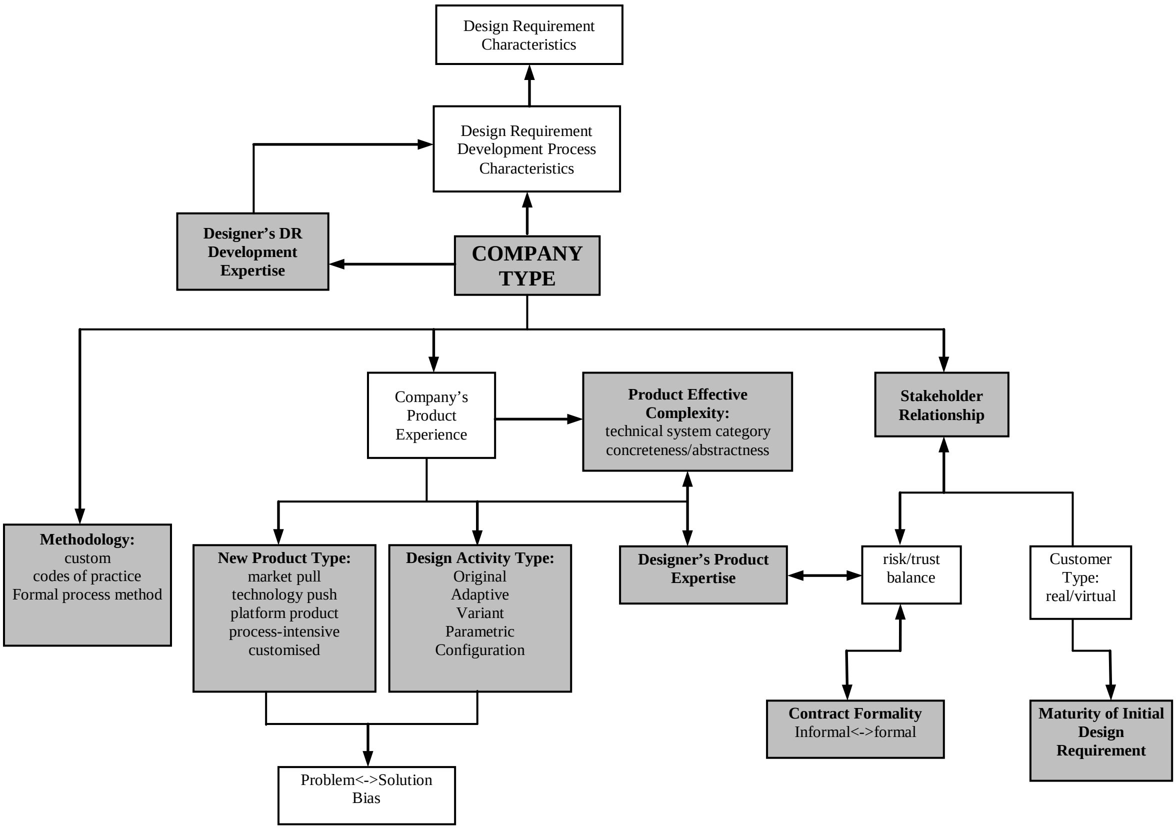


Figure 2.14 The principal and interconnected factors that affect the design requirement development process and the design requirement from Darlington and Culley [2004]

Quality Function Deployment (QFD)

One well-known and systematic technique used to generate engineering specifications is quality function deployment (QFD). The QFD method was developed in Japan in the late 1960s by Professors Shigeru Mizuno and Yoji Akao [Mazur 2010]. This method aims to facilitate design engineers to translate customer requirements into design specifications. This method comprises eight steps: 1) identify the customers: who are they?; 2) determine the customers' requirement: what do the customers want?; 3) determine the relative importance of the requirements: who versus what; 4) identify and evaluate the competition: how satisfied is the customer now?; 5) generate engineering specifications: how will the customers' requirements be met?; 6) relate customers' requirements to engineering specifications: how to measure what?; 7) set engineering targets: how much is good enough?; and 8) identify the relationships between engineering requirements: how do they dependent on each other? [Ullman 2003]. According to Ullman [2003], Toyota was able to reduce the cost of bringing a new car model into the market by over 60% and decrease the time required for its development by one-third.

The QFD method has been used for a wide range of applications. Lertchanyakul [2010] reports QFD application in the chemical industry, specifically in helping to understand latent customer needs and incorporating them in the company's new product development and quality assurance process, leading to better customer satisfaction and business growth for the company and their customers as well as the creation of new market opportunities. In education, Boonyanuwat *et al.* [2008] used QFD to develop a curriculum for industrial engineering. Lampa and Mazur [1996] also used QFD to improve airport breakfast service. Johnson and Mazur [2008] presented an application of modern QFD in the design and selection of TRW Automotive's brake system sensor. Despite its advantages, the QFD method has also been labelled time consuming and laborious [van de Poel 2007].

2.2.9 The significance of a design specification in design projects

Specifications are used in a wide range of industries including product development, building, software, etc. The academia and industries have acknowledged the significance of design specification in the product development process due to its multiple roles in procurement, tendering, designing, communication, etc. In the theory of the product development process, the development of a tangible product is based on specifications developed prior to the design process. Usually, the design specification is derived based upon the functional specification developed by the planning department after the market analysis is carried out. Specification acts as a central part in the product development process between design teams, design engineers or different functional teams in the product development company. It also acts as a working arena throughout the product development process between stakeholders [Chakrabarti *et. al* 2004].

Roozenburg and Eekels [1995] point out that a design specification could fulfil two functions: it could provide direction towards the process of generating solutions and normative information for the evaluation. However, empirical research indicates that early planning and specification is a key success factor in new product development [Baxter 1995; Cooper 1993]. Unfortunately, the process of designing a good performance specification (the requirements needed to conceive the product) does not gain enough attention in practice and theory [Roozenburg and Dorst 1991; Hollins and Pugh 1990].

Requirements lists stored in databases or design support systems can assist the retrieval of old orders and designs. Subsequently, they encourage the use of existing documentation as the basis for new projects. Drawing up requirements lists from existing products can also provide a very valuable source of information for the ensuing development and rationalisation of those products. Once compiled, requirements lists act as a very useful store of information about the required or desired properties of the product, and are hence extremely helpful for further development with suppliers, etc. [Pahl and Beitz 1996]. Specification is one of the most vital factors in the product development process since the cost of the total design rises as the design approaches production [Hollins and Pugh 1990].

Performance and specifications are strongly linked, and play a central role in the new product development (NPD) process. Osteras *et al.* [2006] explored this relationship in more detail and categorised it into two groups:

- Forward relationship (performance to specification): The desired performance outlines what is to be achieved in the NPD process. The specification describes how this performance can be achieved (using a synthesis process involving evaluation of alternate solutions to select the best solution) with the desired performance as an input to the process. Thus, the specification becomes a function of the desired performance. Often, there are several alternative solutions yielding the same desired performance. This results in several specifications (defining alternative solutions) and a one-to-many relationship.
- Backward relationship (specification to performance): The actual performance of a product built according to stated specifications will, in general, differ from the desired performance used in the formulation of the specification. The actual performance can be viewed as a function of the stated specification. Note that this is a one-to-one relationship as a set of specification leads to a single actual performance of the product.

A balanced approach to specification is likely to lead to a good product design performance, starting with a clear statement of the requirements of the customer, then an analysis with the aid of a questionnaire/checklist, following which all the key components of the specification are identified. All departments participate in the drafting of the specification which is prepared against a clear statement of the design objectives of the company [Oakley and Pawar 1983].

Ullman *et al.* [1997] state that usually, not everything is known or knowable about the alternatives or the criteria on which the alternatives are evaluated. Nonetheless, the team must choose an alternative based on this incomplete information. As in the conceptual design phase, the alternatives are evaluated against the criteria stated in the design specification. Thus, an effort to ensure clearer criteria for evaluation would be beneficial for finding the best concept.

Specification plays a central role in guiding the relationship between the supplier and original equipment manufacturer (OEM). Quertani and Gzara [2007] explored the link between the design process features and product specification dependencies throughout the entire development cycle. The purpose of this exploration was to ensure that the coordination of design activities can be done more efficiently and effectively in a collaboration design process. In addition, they suggested ways to identify and manage specification dependencies to improve collaborative process performance. Furthermore, they proposed a process traceability tool to track the design process in an ongoing manner. Based on the information captured, the dependencies between specifications involved in the track process were identified and inserted in the dependency network which was maintained throughout the design process. A set of mechanisms was then proposed to qualify the identified dependencies. They concluded that extracting and qualifying specification dependencies is useful in many design situations, for example, during an engineering changes management process to assess impacts and study change feasibility or during a conflict management process to assist designers in resolving conflicts and maintaining the coherence of the design process. The inclusion of the design specification in an integrated product model has the benefit of increased traceability of the design decisions and simplified redesign due to requirement changes [Malmqvist and Schachinger 1997].

2.2.10 Design specification in applications

The roles of a specification are not only limited to designers in carrying out designing tasks but may also be used for many other purposes. For instance, Chen and Pai [2005] employed design specification to devise a methodology for a conceptual design of mechanism. They categorised design specification into three coherent categories, namely functional requirements, structural requirements and design constraints. These categories were later used to guide the construction of functioning kinematic chains, identification of compatible kinematic structures and labelling of the joints in a compatible kinematic structure. As a result, the enumeration of feasible mechanisms was able to be performed much more efficiently during the conceptual design stage. Stober *et al.* [2010] proposed a property-based framework by combining customer requirements, DFX-Aspects and the degree of maturity in order to monitor the development process. This was done to ensure that the cause of iterations can be noticed in the early stage of development, following which an appropriate step can be triggered to avoid an expensive iteration. Chen and Lin [2002] also used functional requirements and constraints for the optimisation of product configuration design. Based on the role that specification might play in outsourcing decisions, Nellore and Söderquist [2000] proposed a new outsourcing model for guiding outsourcing decisions in terms of the specification generator, type of supplier and contract relationship. They found that the role of specification in outsourcing decisions helps to connect different functions and people, facilitate cross-functional communication and align the entire company in the same direction. Finally, they found that utilising specification in outsourcing decisions would make those decisions much more visible throughout the organisation.

2.2.11 Specification changes during the design process

An individual requirement is not static throughout the project but changes in one or more steps. Requirement changes are often preceded by oral discussions, hypothetical testing and consideration of proposals before being formally agreed on and documented in the specification. This is a natural process since prerequisites are often changed and knowledge is gained throughout the course of the project [Almefelt *et al.* 2006].

Design requirements may change for a variety of reasons, and could drastically impact the design of the product [Hintersteiner 2000]. However, the fundamental issue is how the changes are addressed during the design stage. Gero and Kannengiesser [2006] outlined the reformulation type for addressing change during the design stage. They decomposed change reformulation into three types: the structure level, the behaviour level and the functional level. However, an empirical study carried out by McNeill *et al.* [1998] confirmed that reformulation at the structure level is the predominant type of reformulation in the design course. The same study also discovered that reformulation at the behaviour level and functional level does occur but decreases during the design process.

Requirements are changed, added and reprioritised throughout the course of the product development process. Underlying factors for changes in the requirements specification include knowledge gained through the development work (e.g. through testing), requirements found to be conflicting, technical difficulties in meeting a high specification, opportunities for function-sharing and synergies, unexpected demands for cost savings, new legal requirements and unexpected competitor situations and customer preferences, resulting in changed market requirements [Almefelt *et al.* 2006].

The three main reasons for changing requirements are technological evolution, competitors and customers [Fricke *et al.* 2000]. However, changes in specifications still occur even when the design process is already completed. This is regarded as a problem because too many changes means rework and delays in the product development process. Major delay and cost problems are to be expected if the changes in specifications are made after the production tooling is already set up. Customers may not always be clear about what they want, and therefore their requirements may be underspecified and subjected to change later on [Hintersteiner 2000]. In another case study, Ahmed and Kanike [2007] found that changes in specification occurred after the original design was completed, and the majority of changes arose during the manufacturing/building and testing phase. Gries and Blessing [2006] point out that a typical failure at lower levels of design is the ignorance of contradicting requirements. Efficient coordination of design activities relies on a thorough understanding of the dependencies between shared product specifications throughout the entire development cycle [Ouertani and Gzara 2007].

A reasonable set of requirements cannot be firmly established without understanding how different parts of the design interact with one another. This highlights the potential impact that a requirements change may have for the overall product. Thus, the earlier the requirements can be accurately specified and classified, the better the downstream process will be. According to Ertas and Jones [1993], "if the design requirements are too stringent, the project cost will escalate and possibly no supplier will be found that is willing to bid on the contract to provide the item in question". If the requirements are too lax, the overall system requirements may not be met which could lead to dire consequences for the entire project. An additional problem with loose requirements is that they end up being tightened with greatly increased cost, difficulty and ill will between the supplier and the customer. The importance of establishing valid design requirements is thus apparent. A good design specification will minimise problems of interpretation that could surface later and result in disagreement with the supplier, possibly with negative impact on the entire project. In the early stages of a project, it is not always possible to make precise statements in the requirement list. The statements have to be amended or corrected during the design and development process [Pahl and Beitz 1996].

In engineering design, the purpose of the design requirement evolution process is to arrive at a complete, concise and correct description of the design need, expressed essentially in natural language. From this description, a successful design can be found [Darlington and Culley 2002]. Design requirement can never been completed; designer engineers must establish requirements for additional properties for the technical system intended to solve a design task [Hubka and Eder 1988]. The result of an empirical case study found that the difficulties faced by design engineers during the task clarification were the fact that the customer changed the requirements and the requirements were formulated too late [Romer *et al.* 2001].

The design is thought to consist of three logically and temporally distinct stages: the stage of analysis of the requirements, then the stage of synthesis followed by the stage of evaluation. Analysis is described as involving the identification of all possible factors that may be relevant to the given design situation, determination and resolution of all interactions among the factors and the eventual reduction of these factors to a complete set of specifications. Meanwhile, synthesis involves the construction of partial solutions for each distinct specification and the integration of these partial designs into a complete form. Finally, the evaluation phase is concerned with testing the design produced during the synthesis phase against the specifications identified during the analysis phase. In the event that alternative forms were produced during synthesis, this is also the stage in which the choice is made between the alternatives as a result of evaluation. Several instances of these three phases may be required in order to progress from an abstract level to a more concrete level. The design process is naturally iterative; the designer repeatedly goes back to refine and improve the design until the design satisfies the requirements [Maimon and Braha 1996].

Four different types of requirement changes have been learned from the analysis and observation of data of Maher and Tang [2003]:

- Adding new problem requirements: a design problem is now known as an ill-defined problem without clear problem requirements in the beginning, hence designers generally find new problem requirements during the design process.

This kind of change in requirements is named "adding new problem requirements", which extends the boundary of the space of problem requirements.

- Refining problem requirements: the initial problem requirements are often modified according to how designers apprehend and reframe the design problem. This kind of change is named the "refinement of problem requirements" which refines the information within the original bounds of the space of problem requirements.
- Searching for new problem requirements: designers' efforts to find new problem requirements are not always conclusive; it is a search process without immediate results.
- Re-examination of problem requirements: the initial problem requirements must be generally fulfilled no matter how the design requirements are interpreted during the design process. Consequently, designers often re-examine the initial problem requirements to assure their fulfilment. These periods are regarded as a "re-examination" of problem requirements.

Based on an empirical study, Blessing [1994] found that several requirements along with the initial problem statement were reformulated or had to be reformulated during the design project. In most cases, this resulted in a reduction of the required functionality which was initially very broad. This was partially possible because the system would become part of a new product range, thus allowing certain features to be transferred to future products. In addition, the study found that five major changes in the specification were carried out during the development of a product which caused large modifications. The last major change took place only a few months before production.

2.2.12 Research about design specification

Darlington and Culley [2004] investigated several design cases in industries in order to gain a better understanding of how design engineers in industries actually go about developing design requirements, how the circumstances in which they operate have a bearing on this process and how the discipline in which the design is being carried out influences the process and content of the resulting design requirement. Together with insights gained from scrutiny of the work of design methodologists and a literature review of design requirement research, the findings of this investigation were used to derive a model of factors that influence the design requirement development process and the design requirement itself (refer to Figure 2.14).

Through these studies, Darlington and Culley also recognised the difference between the idealised notion of design requirement capture as described in the design methodology [Ullman 2003; Pugh1997] and the reality of its capture in industrial practice. They discovered that the characterisation of the client types reflects the way the design requirement process works because the clients approach the company with varying degrees of clarity about the design task that they are asking for. Thus, they classified the clients into three major categories that reflected the state of the client's specification:

- Haven't got a clue: These customers brought problems that were expressed in the simplest ways, with very little prior thought to the detail requirements. As a result, the company is required to expend considerable effort in developing the requirement from the initial statement of need into a design requirement that can form the basis of a contact.
- Semi-developed: Here, sufficient thought has been given to the requirement so as to provide a useful starting brief. The design requirement might include references to solution domains or specific physical aspects of the solution.
- Full specification: This type of the design requirement is fully specified by the customer and expressed in contractual terms. There is no requirement for further development of the design requirement before design work can begin, although clarification of elements may be required.

Furthermore, they found that the design requirement development process and the content of the design requirement rely on several factors including:

- The nature of mechanical and electronic/software engineered products, and the influence of the real world on the activity of the design process.
- The case-specific nature of the project such as the modification of an existing product to fulfil economy demand, short time-to-market, dependency on use of existing parts, the design requirement being frequently less detailed and implicit at the components level. However, most of the requirements are expressed in terms of the solution.
- Customer/designer relationship which is based on the customer's trust in the design engineers. This judgment starts from the customer's perception of the knowledge and capacity of the design engineers.
- The multiple roles of the design requirement. The case studies suggest that the design requirement has two principal roles: serving as an agreement about what is desired in an end product, and providing a basis upon which the designer can proceed in synthesising a solution. These roles influence the way the design requirement is developed and recorded. However, the more predominant factors that influence the design requirement's content are the politics and social context in which the development takes place.

Almefelt [2005] studied design requirements in an automotive manufacturing company. Five major issues regarding design requirement in the industrial practice were revealed from this study including:

- A strong focus on requirements can be seen as essential for the creation of good products. At the same time, excessively forceful and formalistic striving to fulfil them might result in sub-optimisation or project stagnation, since in practice requirements are often incomplete or conflicting.
- In practice, individual requirements are not static throughout the project but change in one or more steps. Requirement changes are often preceded by oral discussion and hypothetical testing of solutions before a formal agreement and documentation is agreed upon in the specification. This is a natural process since prerequisites are often changed and acknowledgement is gained over the course of the project.

- The follow-up of requirements and their fulfilment has shown to be more problematic to manage than the requirement specification itself. It is apparent that the priority given to different requirements in a practical work situation does not adequately mirror the requirement specification or the emphasised central purpose; instead, it mirrors the resources of different organisational disciplines or focus of approaching the tollgate. It can also be pointed out that requirements that are not actively promoted seem to be implicitly suppressed.
- In the industrial context studied, the balance between the performance and cost is seen as the central factor to pay intention when developing and selecting design solutions. At the same time, balancing performance and performance/cost ratio is a well-known difficulty, and a number of structured methods are used with the aim of evaluating and selecting solutions in relation to strategic requirements. It is also evident that daily work is central for step-by-step development of a balanced solution. Nonetheless, there is evident potential to improve working practices for balancing requirement and solutions. For instance, requirements settings, design selections, late changes and cost savings are often made with limited consideration of overall system solutions, total property content and overall performance/cost ratio.
- Requirements can drive innovation forward presuming that they are well-justified in relation to a forward aiming intent and continually assessed with reference to new opportunities.

Almefelt *et al.* [2006] also found that the most significant problem related to the interpretation of requirement specification was due to the requirements not being clear enough. Regarding the detail level of which requirements should be broken down, there are considerably differing opinions among respondents as well as in the mind of each individual. An overly detailed breakdown of requirements may result in too many requirements and subsequently inhibit optimization and creativity. A less detailed breakdown may better allow the utilisation of supplier competence but may also result in differing interpretation and misunderstandings. In essence, as evidenced by the interviews, the issue is a matter of how firm the desire is to manage the development work and trust in the development team or the supplier [Andreason 2003].

Darlington and Culley [2002] compared the task of developing the design requirement in the software and information system domain with the engineering domain. This study aimed to initiate a discussion of the extent that the substantial body of research in software requirements engineering might help in providing an understanding of the design requirement for the engineering design domain. A tentative characterisation of the differences between the tasks in these two domains was determined including e.g. in engineering design domain, customer needs refer to a mixture of concrete and abstract object whereas in software engineering domain the customer needs predominantly refer to abstract objects. They also suggested overlapping areas between the domains that need further study.

Specifications play a central role in guiding the supplier-OEM relationship. For so-called "black box" parts, the OEM specifies overall requirements for product function and performance, cost target and development lead time, and then communicates this information to the supplier who performs detailed engineering and testing. Black box engineering marks a fundamental change in the buyer-supplier relationship [Karlsson *et al.* 1998]. Karlsson *et al*. also found that the specification becomes an open medium for communication between suppliers and OEM.

Furthermore, Karlsson *et al.* [1998] highlighted the most important implications regarding the design specification and its role in the context of the OEM-suppliers relationship:

- The design specification cannot be regarded by suppliers as a fixed document, but should instead be regarded as an open arena for technical adjustment.
- OEMs often give ambiguous design specification to suppliers because of internal functional conflicts (e.g. in marketing, engineering and purchasing).
- The pro-activeness of the suppliers was observed to have a positive effect on the specification process.
- Integrated component development already begins at the specification stage.
- Changes in specification are unavoidable in any engineering project and it does not deserve to be seen as a waste of time, money and engineering efforts.

The specification process in new product development is critical for obtaining a high quality, low cost and well-interfaced product. However, despite the rich literature on product development, specification management has been given less intention. Nellore *et al.* [1999] carried out a comparative study of the specification development process between one auto and one aircraft original equipment manufacturer (OEM) located in Europe. The objective of the study was to explore the important constituents of specification model and to improve relations between the OEMs and the suppliers during the specification process. A model of specification management that identifies important steps from conceiving the idea to delivery was developed.

Despite all the best efforts done, the design process often leads to the introduction of products that do not meet customer expectations. Although the design team typically applies customer-related information from several sources, the product somehow fails to satisfy customer requirements. Clearly, this is essential to develop a better understanding of the process by which designers in large development organisations transform information about customer requirements into the final design specification. Thus, to improve understanding about this process, Bailetti and Litvia [1995] examined design managers' perspectives about the sources of customer requirement information. They found that during the evolution of a product design, the design team applied information endorsed by marketing and product management. Common sources of such information include commercial specification, inferences from existing products and services, deployment studies and external standards. However, this information was deemed inadequate; designers supplemented it by creating and sharing their own customer-related information. This local information includes the results of benchmarking function and performance, the designers' perception of a service provider's installation based on the equipment and validation of intermediate designs.

Traditional requirement definition activities begin with the engineer or design team performing a needs analysis to identify user requirements as noted by Asimove [1962] in Eodice and Leifer [2000]. While recent studies have focused on conceptual design activities, research into the requirements definition process has, for the most part, been lacking. Needs analysis is generally subjective and varies according to the composition and experience of the design team. Systematic procedures for defining and ranking requirements could consolidate the foundation on which the design process is predicted, and enhance its outcome by providing the designer with a consistent, reliable approach product development as stated by ASME [1986] in Eodice and Leifer [2000]. Before such systematic procedures can be developed, it would be necessary to establish an understanding of the existing process by which requirements evolve, and to create a model evaluating this process. For this purpose, Eodice and Leifer [2000] conducted a pilot study by analysing requirements using the problem reduction method. They concluded that the method of problem reduction using AND/OR graphs proved to be an effective framework for analysing requirement evolution.

Nidamarthi *et al.* [1997] studied the ways in which designers understand design problems and how such understanding affects the design itself. They found that better understanding along with better problem-solving might lead to a better product. During observation of the design process of two designers, they found that requirements influenced solutions in their generation, evaluation and selection and so forth. Meanwhile, according to Ehrlenspiel and Dylla [1989] designers' problem understanding will be better if they are willing to analyse requirements in greater depth.

Chakrabarti *et al.* [2004] presented the results of an empirical study based on real time protocol data about the design processes of four experienced designers. The objective of this study was to understand how requirements are identified, clarified and used in the design process, and how these influence the quality of its outcome: the emergent design. The results indicated that the quality of the activities and methods used had a strong impact on the quality of the emergent design in terms of its degree of fulfilment of the requirements.

A product's design specification is an important element in product development projects because it defines the target to be met. One requirement is to articulate and communicate the aspects which make the product attractive from the users' viewpoint. This is based on the underlying assumption that it is meaningful and the only feasible approach to interpret the results of a need analysis into a set of technical specifications which express the customers' need and perception of value. Hansen and Andreasen [2004] examined this assumption to outline the roles and tasks of product design specification. They also identified existing theory elements to build a distinct theory of product design specification.

The importance of customer requirement management in product development has been well-recognised in both academia and industries alike. Jiao and Chen [2006] reviewed state-of-the-art research in requirement management. According to their results, customer requirement management entailed various issues related to requirement elicitation, analysis and specification as well as the requirement management process. With respect to a holistic view of customer requirement management, key challenges and future research directions were identified.

A product is designed with the purpose of processing certain properties which are prescribed as requirements in the design specification. Salonen *et al.* [2005] investigated the evolution of property predictability during the early phases of design in a case study context. By the term ‘property predictability’, they referred to the designers’ confidence in predicting product properties based on the information available. In the case study, with the use of the produced design models at four different stages of concept concretisation, the designers evaluated their confidence in predicting product properties related to the requirements set for the task. As a result, they identified three different patterns of property predictability behaviour. These patterns consisted of properties of which predictability was relatively high throughout the early phases of the design process. Properties of which predictability showed a high increase during the progression of the early phases remained relatively low throughout the design process. Size and appearance was a requirement class where the level of property predictability was perceived as relatively high throughout the early phases. The technical, manufacturing and assembly and service requirement classes showed a noticeably high increase in property predictability between the group stages of concept concretisation. Meanwhile, feasibility and product life cycle requirements remained relatively low throughout the early phases.

The role of contracts in validating specifications has been neglected in research as they are often thought of as commercial and legal documents with little value as far as validation is concerned. To demonstrate the role of contracts in validating specifications, two in-depth case studies were carried out in one auto and one aircraft original equipment manufacturing located in Europe [Nellore 2001]. Data were collected through participant observation, interviews and analysis of archival sources.

As a result, a strategic contract structure encompassing two categories of elements, the validation criteria for entry and the validation criteria for remaining in the business was proposed. The strategies contract structure can aid managers involved in the specification process to structure development projects with suppliers to attain the planned goals.

Catic and Malmqvist [2010] studied an industrial case with regard to requirement management in the commercial automotive industry. Several notions about formulation requirements were derived from this study. With regard to solution synthesis and to enhance creativity, the participants proposed the formulation of quantitative requirements at regular intervals. In respect to the difficulties of requirement formulation, the problems that resulted were due to lack of background and context for each requirement, and the relation between requirements was unclear in the top-down flow and at the same level. Lack of understanding between design actors may also cause difficulties in defining product specification. Improving shared understanding amongst design actors about functional requirements is thus essential.

As the initial stage in addressing this issue, Arikoglu *et al.* [2010] investigated the effectiveness of scenarios in improving shared understanding of functional requirements between design actors. They found that the usage of scenarios reinforced understanding amongst the design actors.

Shinno *et al.* [2006] analysed the characteristics of design information related to product specification using a simple mathematical method. The actual design information used in this analysis was obtained from focused interviews and questionnaire investigations with mature designers within leading machine tool manufacturing companies in Japan. In the process of mechanical design, tolerances are of crucial importance because decisions related to them can have a decisive influence in terms of product cost and quality. At present, there are numerous approaches and investigations related to the analysis and/or synthesis of tolerances and the modelling of assemblies.

2.2.13 Conclusion

This review provides an overview of specification documents and requirements. It can be concluded that the terms ‘specification’ and ‘requirement’ are used interchangeably by different authors in their literature. Thus, understanding the context in which the term is used is essential to understand whether the term used by author refers to ‘an artefact’ or ‘a statement’. Regardless of the term used by authors in the literature, the significance of ‘specifications’ or ‘requirements’ as an important element in the design process is agreed on by all authors because the terms carry the stakeholders’ need regarding the product to be designed.

Acknowledging the role of specification in the design process, several general guidelines and methods have been proposed to develop good specifications. Most of these methods are extension efforts after comprehensive market analysis is carried out. Additionally, criteria for good requirements have been suggested by several authors that are beneficial to design engineers for checking the quality of requirements in a specification. Unfortunately, the basis of development of these methods still lacks empirical evidence.

The review of literature does not cover requirement management and formal model for description of specification due to the following:

- The review emphasis on the issues for the Descriptive Study I (DS1) that are requirement/specification changes, design process model, requirement and deriving requirement for a specification.
- The study does not aim to understand the requirement management in practice in detail as this is not included in the scope of the research.
- The formal model such as SysML during product lifecycle is more useful after requirements have been derived from its origin for better documentation. However in this research how to derive requirement from its origin is the primary concern. After the requirements are derived many other things need to be done such as documenting, analysing, prioritising the requirements and this is the concern of requirement management whereas the study focuses on the deriving requirements from its origin. Thus literature study does not cover requirement management and formal model of requirement description.

2.3 Engineering changes

A review of engineering changes provides the necessary background about the implications along with an examination of its feedback to the development of a good design specification.

2.3.1 Definition of engineering changes

Engineering Changes (ECs) constitute a normal part of a product's life cycle. Engineering changes are viewed in a number of ways. For example, Huang and Mak [1999] define ECs as the modifications of a product or component associated to forms, fits, materials, dimensions or functions. From their point of view, it can be as simple as documentary amendments or as complicated as the entire redesign of products and manufacturing processes.

On contrast, Wright [1997] addresses ECs problems from the production perspective and defines them as modifications made to the component of a product that normally takes place after the product enters the production phase.

ECs are also viewed as alterations made to parts, drawings or software that is already released during the design process. The change can be any size or type, can involve any number of people and can take any length of time [Jarrat *et al.* 2003].

To differentiate between ECs, Lindermann and Reichwald [1998] in Köhler [2008] classified engineering changes by distinguishing them into problem- or innovation-oriented i.e. if the change is an error rectification or aimed at improving the product. On the other hand, Eckert *et al.* [2004] extended this classification by considering the origin of the changes; it is either initiated change or emerging change. Initiated change refers to changes arising from external sources (i.e. customers and legislation) while emergent change means changes arising from the product itself due to an error during the design process. In this respect, innovation is considered part of an initiated change for product improvement.

2.3.2 Studies on ECs in practice

Several studies have been conducted in industries to understand ECs thoroughly. Wright [1997] has reviewed key publications of industrial and academic researches relating to the management of engineering changes. The reviews showed that engineering changes were primarily perceived as problems rather than opportunities. Wright concluded that while this viewpoint was understandable, it failed to consider the effect of engineering changes as part of the product improvement process.

Balcerak and Dale [1991] also studied the issues and problems encountered in managing ECs. They found that people tended to confuse an EC's reason with its purpose. For easy administration, they proposed a scheme for EC classification based on type (the impact of ECs within organisation) and grade (the urgency to address the ECs).

Moreover, Huang and Mak [1998] discussed a number of problems inherent in paper-based engineering change control (ECC). They highlighted the need to have good computer software to resolve these problems. However, beside its availability this software is still not widely used in industries due to various factors: 1) the computer aids are not well-known to ECC practitioners; 2) existing computer aids do not reflect well on ECC practice; 3) this was not customisable and imposes too many commitments to shift from the current ECC practice; 4) comprehensive functionality undermines their focus; 5) impose intensive data requirement; and 6) accompanying documents were not helpful to ECC practitioners. These reasons emphasise the importance for software developers to consider all these issues in developing computer-based support for ECC.

Pikosz and Malmqvist [1998] studied the ECs process in three engineering companies in Sweden. The study focused on specific factors i.e. the implication of the ECs process on the lead time. They also studied the possibility of applying a modern product data management (PDM) system to support the ECs process. The major outcomes of the study were: 1) outlines of a few strategies to improve the engineering change management (ECM) process; and 2) the product data management systems as support to achieve an optimal ECM process.

Huang and Mak [1999] examined several aspects of industrial practices in terms of managing ECs in 100 UK manufacturing companies. These aspects included the systems, organisations, activities, influential factors, strategies, techniques and computer aids. The major contribution of this study was guidelines for good ECM practice.

Huang *et al.* [2003] drew upon the findings from interviews conducted within four Hong Kong manufacturing companies in 1999 to investigate the state of ECs problems and the industrial practice in managing ECs. They examined aspects of volume, sources, and effects whereas the present industrial practice focuses its investigation on documentation, organisation and activities. Two general findings were gleaned from this study: 1) EC is a noticeable problem that cannot be underestimated; and 2) the management of ECs was unsatisfactory in the companies surveyed.

Eckert *et al*. [2004] comprehensively analysed the problems and processes associated with product change. They specifically looked at the potential causes and effects of changes, and analysed the formal and informal processes that were used to manage changes. This descriptive study has led to the development of a computer support tool that gives an indication of the risk of a change affecting other systems. In addition, this study has provided designers and design managers with a greater overview of a given product.

Based on studies in the aerospace and automotive industry, Eckert *et al.* [2006] described the significance of change processes and identified some of their complexities. Furthermore, they described ways to help product designers understand and visualise change propagation. The supports they devised were: 1) probabilistic prediction of the effects of changes; and 2) visualisation of change propagation through product connectivity.

Veldman and Alblas [2007] carried out a multiple case study to uncover the effects of engineering changes on companies' standard products and processes. They found that there are conflicting needs emerging from several parts of the development life cycle.

Ahmed and Kanike [2007] linked the causes of changes to its life cycle phase in their investigation to understanding changes. This study was carried out by analysing 1500 documents on change reports of an aero-engine during its life cycle. They found that the majority of changes occurred during the manufacturing and build phase. Moreover, they concluded that changes to the engineering specification together with meeting design criteria were the major causes during the prototype testing and development phase.

Vianello and Ahmed [2008] analysed 250 documents on change requests for the first two years of service of an aero-engine. The aim of the study was to investigate the causes of changes in the service phase where changes were most expensive. As a result, they emphasised the need for a clear understanding of service phase issues at the earlier phases of a product's life cycle.

2.3.3 Consequences of engineering changes

Customers have ever increasing expectations about the quality and performance of the products that they buy. In order to keep pace with this demand for value, companies in practically every business field have to come up with frequent upgrades of their products. One of the main difficulties in redesigning a product is that a proposed design change can have many undesirable side effects besides the intended ones. In complex engineered devices such as automobiles, these side effects are often hard to predict, especially when they cross the boundaries between the device's sub-systems [Ollinger and Stahovich 2001]. Each engineering change generates a level of impact on costs, time to market, tasks and schedules of related processes. A study to investigate the impact of ECs on material planning was carried out by Wanstrom and Jonsson [Wanstrom and Jonsson 2005], impact on cost by Oduguwa *et al.* [Oduguwa *et al.* 2006] and impact on the design process by Terwiesch and Loch [Terwiesch and Loch 1999].

According to Eckert *et al.*, the later the change occurs in the design process, the more costly the change becomes. This is due to the fact that the process becomes more time critical and the product become more integrated [Eckert *et al.* 2004]. Consequences of ECs have been reported in a number of studies. ECM consumes 30 - 50%, and sometimes up to 70% of production capacity [Lindermann and Reichwald 1998] in

Köhler [2008] and represents 20 - 50% of tool costs [Huang and Mak 2003]. Clark and Fujimoto [1991] reported that 20 - 40% of die development costs in vehicle development, is caused by ECs. Therefore, the company has to ensure that ECs are implemented efficiently to reduce lead times and costs. This highlights the significance of devising supports (techniques, tools, etc.) to manage ECs. However, in order to provide such support, it is crucial to understand the company's difficulties in dealing with ECs which also cause disruptions in the manufacturing function of a firm. These disruptions include delays or backorders in the delivery of both committed orders and forecast demands of an existing product [Balakrishnan and Chakravarty 1996]. Balcerak and Dale [1992] identify poor ECs control as a major contributing factor to the low bill of material (BOM) accuracy.

2.3.4 Engineering Change Management (ECM)

Engineering changes are part of any design process. Changes are often requested even before a product design has been completed. However, change requests during an ongoing design process are difficult to assess because the design is still evolving. Some parts may be easy to change where only conceptual designs exist; other parts may already be frozen and hence more difficult and probably more expensive to change. In order to find the best way to implement a change at a given time, the designer needs to be aware of not only the design and the interactions, but also of the state of development of every part. However, many designers are not always aware of all interactions and, hence, unexpected and expensive change alternatives are chosen. In response to this situation, Eger *et al*. [2007] have devised a tool to evaluate change proposals during ongoing design processes by taking into account the state of the development of parts. In addition, the link between the product, process and people that interact during product development and factors that make change implementation risky and lead to increased change costs were also considered.

Many complex products are now developed collaboratively across enterprises in a geographically extended and time extended process. High frequency changes to the initial design requirements are typically requested due to service needs, legislative directives and market feedback. Responding to requirement change requires a cost impact analysis. Thus, a methodology to determine costs rapidly and accurately for requirement changes, particularly during the design development phase of the life cycle development of a complex product, is required. Oduguwa *et al.* [2006] proposed a two-stage technique to analyse the impact of changes on cost, namely: 1) identifying the design parameters that are likely to be affected; and 2) predicting the incurred cost for possible design changes using a rule-based approach.

It is essential to assess the effects of change rigorously before a change is implemented, yet design engineers are faced with the problem that an exhaustive analysis of all product parameters affected by change proposals is simply impractical. Ariyo *et al*. [2007] described a criticality-based approach to predict risks of changes in priority form. This technique uses the Change Risk Prioritisation Number (CRPN). It enables product designers to identify components and concentrate their efforts on components that are critically disposed to the effects of changes.

Flanagan *et al.* [2003] developed an analysis method to determine how change propagates through function within the product. Their method used the Design Structure Matrix (DSM) to illustrate change propagation paths and highlight the connections. The method provides the user with an in-depth knowledge of function connectivity within a product. Meanwhile, Clarkson *et al.* [2001] developed a prototype computer support tool to predict the risk of change propagation in terms of likelihood and impact of change. Keller *et al.* [2005] also introduced several ways to view change propagation data through CPM (Change Prediction Method), a software tool for predicting change propagation. The tool enables designers to run what-if scenarios in order to assess the implications of changing components in a complex product during the design process.

Keller *et al.* [2006] also introduced several heuristic methods for change propagation assessment in complex products. These methods are based on simple graph theory. These heuristics methods were developed based on the length of the shortest path, the edge connectivity and the number of common neighbours of two components in the product connectivity model. They found that the longer the shortest path between two components, the less probability of change to propagate. The higher the edge connectivity between two components, the more likely changes will propagate to each other and the more common neighbours two components share, the more likely change propagation becomes.

Visualising connectivity and change propagation in complex products is difficult but nevertheless a key for successful design. Several stakeholders such as designers, managers and customers have different viewpoints on the designed artefact and require different information. Multiple views provide a means to visualise complex information and are also a way to fulfil the demands of different user groups. In order to justify a particular design change as feasible or desirable, it is necessary for the designer to have knowledge about the side effects of the proposed change because very often, the side effects can outweigh the benefits expected from redesign. To facilitate engineers in making a quick yet accurate assessment of the overall effects of a particular design change, Ollinger and Stahovich [2001] have developed RedesignIT - a computer programme to generate proposals to achieve redesign goals, identify side effects (potential or certain) and suggest additional changes to counteract those effects. These proposals describe how the design parameters could be changed to achieve a specified performance goal. In addition, the programme proposes complementary modifications that may be necessary to counteract the undesirable side effects of the primary changes. The programme helps the designer to understand the possible consequences of a redesign before resources have been committed to detailed design tasks, prototyping and testing. This kind of tool is particularly useful for making modifications to large scale engineered systems where it is not possible for one designer to know all aspects of the design. This work demonstrates the usefulness of causal influence models for planning redesign projects. The advantage of this representation is that it directly focuses on the mechanism by which a design change propagates through a system. It also enables a programme to detect possible side effects of a design change and to identify means of remedying those side effects.

When designing complex products such as robots or jet engines, companies face the problem of designers lacking the necessary tools to predict the behaviour of the product in the case of component change, and to assess the risks associated with decisions. Product models allow companies and individual designers to reason about product properties. The information in the model can be used to analyse the properties of a product before decisions are made about potential modifications. To meet time and budget constraints, it is vital to have the ability to predict the risks of knock-on effects before a change is implemented and to select alternative changes accordingly. Keller *et* *al.* [2007] compared two product models, the Change Prediction Method (CPM) and the Contact & Channel Model (C&CM). Both models showed their capability in assessing the impact of knock-on changes on the design of a complex product. Both approaches can individually guide designers in industries towards high-risk component connections. To overcome some of the shortcomings of both models, two combined strategies were proposed with the aim of providing more information i.e. functional information that is provided in C&CM to increase the understanding of a system, thus improving the decision-making process by providing a larger information background of the system.

Product life cycle stages are inter-related and mutually constraining. Due to the sequential nature of product development processes, some constraints or conflicts may emerge in a later stage and require modifications to the decisions made in earlier stages. The iterations between stages are hence unavoidable and must be managed carefully to maintain the consistency, integrity and validity of product information models. Due to inter- or intra-stage relations, a chain of changes is very likely to occur as the consequence of an initial change. Modelling and maintaining these relations are important in collaborative engineering to evolve the state of the whole product model in a consistent manner.

2.3.5 Strategies to address changes in the early phase of product development

Product architecture is the scheme by which the function of a product is allocated to physical components; it determines how the product can be changed. Ulrich (1995) defined the architecture of a product as: 1) the arrangement of functional elements; 2) the mapping from functional elements to physical components; and 3) the specification of the interfaces among interacting physical components. The architecture of a product determines which functional elements of the product will be influenced by a change to a particular component (to predict change propagation) and which components must be changed to achieve a desired change to a functional element of the product. In general, there are two types of product: modular and integral. Modular products allow each functional element of the product to be changed independently by changing only the corresponding component whereas full integral products require changes to every component to effect change in any single functional element. Therefore, the architecture of a product is closely linked to the ease with which a change to a product can be implemented [Ulrich 1995].

The characteristics of product architecture can have different implications for a firm's product strategy. In fact, a modular architecture seems more appropriate when firms want to emphasise product variety, change and standardisation since a product with a modular architecture does allow firms to change the product by upgrading or adding modules without changing the remainder and therefore keeping that change 'isolated'. An integral architecture may instead be more appropriate when product performance represents the main concern of a firm's product strategy. Therefore, firms have a certain degree of latitude in choosing product architecture. These decisions are subjected and linked to issues related to the firm's strategy, in particular to product performance, product change, product variety, component standardisation, manufacturability and project management. In other words, products may lend themselves to either modular or integral architecture according to the firm's product specific strategy. The designers thus have some degree of freedom in choosing the most appropriate architecture to meet the firm's goals [Prencipe 1998].

In the Design for Changeability approach, Fricke and Schulz [2005] incorporated change considerations early into the design to prevent change propagation. Meanwhile, in an axiomatic design developed by Suh [2001], change and change propagation are minimised by lessening product complexity through the reduction of connectivity between parts. ECs are sometimes necessary due to manufacturing issues i.e. reducing manufacturing costs. One of the ways to reduce changes due to manufacturing issues is providing the opportunity for design engineers to gain manufacturing experience in practice [Baruch *et al.* 1993].

2.3.6 Conclusion

The review shows that ECs have a significant impact on the product development process, both positively e.g. increasing product variants, and negatively e.g. increasing lead time. Proper management of the changes process is essential for companies to take advantage as the changes occur. However, methods to reduce the number of changes during the development of a product, for example the number of changes carried out in the same version/variant of product during its development, need to be addressed as well. Since changes may result due to changes in a specification, an understanding of the characteristics of these changes is necessary for good feedback to develop a specification at the beginning of the design process.

CHAPTER 3: RESEARCH METHODOLOGY

This chapter describes the overall research strategy adopted in this research project, specifically the Design Research Methodology (DRM) framework. In the beginning, various issues concerning the selection of a methodological approach for Descriptive Study I (DS I) are discussed for consideration. Then the relationship between the phase for planning the research and the DRM framework is shown in Figure 3.2. Finally, details of the data collection methods and data analysis methods for the three studies during the Descriptive Study I (DS I) stage of this research are described in sections 3.7, 3.8 and 3.9. Methodology for Prescriptive Study (PS) and evaluation of design support are described in Chapter 5.

3.1 Approaches to Methodology

One way of approaching a research methodology is to evaluate the research either with a qualitative or quantitative approach. The qualitative research method focuses on words to describe reality, relies on observations of the phenomenon and attempts to explain the phenomenon in its natural setting. In contrast, the quantitative research approach grows from a strong academic tradition that trusts in numbers that represent opinions or concepts [Amaratunga *et al.* 2002]. Yin [2002] outlined the elements to be considered in selecting a research approach such as the philosophical position of the researcher, basic beliefs of the researcher about the nature of reality, the research object, the research strategy and its relationship to existing theory. Philosophical assumptions about the nature of reality are crucial to understanding the global perspective from which the study is planned and carried out as emphasised by Krauss [Krauss 2005].

The two main theoretical paradigms for research are positivism and anti-positivism (interpretivism). The positivism paradigm views the reality as objective, and true reality is neither unchanged nor independent from the researcher. Logical positivism uses quantitative and experimental methods to test hypothetical-deductive generalisations. In the anti-positivism paradigm, the reality is subjective as people experience reality in different ways and this is dependent on the people who experience, construct and interpret the reality through their interactions in the social system. Interpretivism inquiry uses qualitative and naturalistic approaches to understand human experience in a context-specific setting [Amaratunga *et al.* 2002]. Thus, knowledge is established through the meanings attached to the studied phenomena. Researchers have to interact with the subjects under study, i.e. the design engineers, to obtain data, and this inquiry will change both the researcher and the subject. Meanwhile, knowledge is context and time dependent [Coll and Chapman 2000]. This approach tries to understand and explain the phenomenon rather than search for external causes or fundamental laws [Easterby-Smith 1991].

Amaratunga *et al.* [2002] summarises the main differences between the positivism and interpretivism paradigm as shown in Table 3.1 based on key features identified by Easterby-Smith [Easterby-Smith 1991].

Table 3.1 Key features of the positivism and interpretivism paradigm [Amaratunga et al. 2002]

Theme	**Positivism Paradigm**	**Interpretivism Paradigm**
Basic belief	• The world is external and objective • Observer is independent • Science is value-free	• The world is socially constructed and subjective • Observer is part of what is observed • Science is driven by human interests
Researcher should	• Focus on facts • Look for causality and fundamental laws • Reduce phenomena to simplest elements • Formulate hypotheses and test them (deduction)	• Focus on meanings • Try to understand what is happening • Look at the totality of each situation • Develop ideas through induction from data
Preferred method in the research	• Operationalizing concepts so that they can be measured • Taking large samples	• Using multiple methods to establish different views of the phenomena • Small samples investigated in depth over time

The review of the research paradigm shows that the choice of research approach is closely related to the research paradigm and the aim of the research is directly associated with the nature of the research questions. According to Yin [2002], the nature of the research questions can be classified into one of the following: exploratory, explanatory or descriptive, as described in greater detail below.

Exploratory research is conducted in a research area where there are remarkably few or no previous studies about the research problem. This type of research aims to look for ideas or hypotheses rather than to test or confirm a hypothesis. The focus of exploratory research is to gain insight about the object of a study for a thorough investigation at a later stage.

Descriptive research is carried out to describe the phenomena as they exist. This research is done primarily to identify and obtain information about the characteristics of a particular problem. Descriptive research goes into further detail when investigating a research problem compared to exploratory research as it is undertaken to determine and describe the characteristics of the relevant issues.

Explanatory research is carried out as a continuation of descriptive research. This type of research goes beyond merely describing the characteristics of a phenomenon but aims to analyse and explain why or how the phenomenon being investigated is happening. Thus, explanatory research aims to understand certain phenomena to discover and measure causal relations among them. An important element of explanatory research is identifying and controlling the variables in research activities as this permits a better explanation of the variables or the causal links between these variables. A variable is a characteristic of a phenomenon that can be observed or measured.

Yin [2002] distinguishes five forms of research questions: 'who', 'what', 'where', 'how' and 'why' questions. As argued above, the research questions strongly influence the choice of research strategy, which is either qualitative or quantitative. Yin specifies the questions in the following way:

- 'What' questions, in the sense of 'how much' or 'how many', refer to number i.e. quantitative data. The most appropriate research strategies are surveys or archival analyses (for example, the study of financial data for a large number of companies in databases).

- 'How', 'why' and 'what' questions of an exploratory kind are, on the other hand, concerned with coming to terms with the meaning, not the frequency, of a certain phenomenon, i.e. the qualitative data and quantitative data approach to analysis.

Returning to the research paradigm (anti-positivism was chosen) and research questions for this research project (see Table 3.2), the 'how' and 'what' questions in this research aim to gain insight about changes in specification during the product development process. As the study is exploratory in nature, a qualitative research approach with an emphasis on meaning was selected rather than the quantitative approach with emphasis on prevalence.

Table 3.2 The research questions

Overall Research Question 1: How do Engineering Changes (ECs) that are a result of changes in specification affect the product development process and provide valuable feedback for the development of a specification document?

Sub-Research Questions:

(1) How significant is the impact of change in requirement towards Engineering Changes (ECs) during the product's life cycle?
(2) What can be learnt from changes in requirement in order to develop a better specification (specification with fewer changes) at the start of the product development process?
(3) How is the development of a specification carried out for a project?

Overall Research Question 2: How can we ensure that all the important design issues are addressed and translated as requirements in a specification?

Sub-Research Questions:

(1) How do specification developers formulate requirements for a specification?
(2) What is the process undertaken by design engineers to understand the design problem at the start of the product development process?
(3) How do design engineers address and translate the design problem to a list of requirements for any one project?

3.2 Approach to research strategy

According to Yin, the type of questions posed, the extent of control that an investigator has over actual behavioural events, and the degree of focus on contemporary as opposed to historical events are the conditions to be considered when selecting a research strategy. In addition, a research strategy should be chosen as a function of the research situation [Yin 2002].

Yin [2002] defines five different research strategies: experiment, survey, archival, analysis, history and case study. Yin argues that all these strategies can be employed to carry out research on different research objectives whether they are to explore (exploratory study), to describe (descriptive study) or to explain (explanatory study). Figure 3.3 maps out the three conditions identified above to the most common research strategies.

Table 3.3 Relevant situations for different research strategies [Yin 2002]

Strategy	**Form of Research Question**	**Requires Control of Behavioural Event**	**Focuses on Contemporary Events**
Experiment	How, why?	Yes	Yes
Survey	Who, what, where, how many, how much?	No	Yes
Archival analysis	Who, what, where, how many, how much?	No	Yes/No
History	How, why?	No	No
Case study	How, why?	No	Yes

A case study is an empirical inquiry that investigates a phenomenon within its real life context, especially when the boundaries between the phenomenon and its context are not clearly evident [Yin 2002]. Data is collected from a small number of organisations through methods such as participant-observation, in-depth interviews and longitudinal studies. The case study approach seeks to understand the problem being investigated. It provides the opportunity to ask penetrating questions and to capture the richness of organisational behaviour, but the conclusions drawn may be specific to the particular organisations studied and thus may not be generalisable [Gable 1994].

The survey approach refers to a group of methods which emphasise quantitative analysis. Here, data for a large number of organisations are collected through methods such as mail questionnaires, telephone interviews or published statistics. The data is then analysed using statistical techniques. By studying a representative sample of organisations, the survey approach seeks to discover relationships that are common across organisations and hence provide generalisable statements about the object of a study. However, the survey approach often only provides a ‘snapshot’ of the situation at a certain point in time, yielding little information on the underlying meaning of the data. Moreover, some variables of interest to a researcher may not be measurable by this method (e.g. cross-sectional studies offer weak evidence of cause and effect) [Gable 1994].

The experiment strategy is a systematic and scientific approach to research in which the researcher manipulates one or more variables, and controls and measures any change in other variables. Experimental research is often used where:

- There is time priority in a causal relationship (cause precedes effect).
- There is consistency in a causal relationship (a cause will always lead to the same effect).
- The magnitude of the correlation is great.

Revisiting the research questions (see Table 3.2) and the three conditions (see Table 3.3), *the case study approach* was adopted as a research strategy for this study. Specifically, the phenomena to be investigated will be in its real life context. No control over the investigated phenomenon is required.

3.3 Choice of data sources

The sources of evidence in Table 3.4 are the ones most commonly used in case studies: documentation, archival records, interviews, direct observation, participant observation and physical artefacts. According to Yin [2002], no single source has a complete advantage over the other. Therefore, a good case study will use as many sources as possible as adopted in this research. After reviewing the strengths and weaknesses of each data source as shown in Table 3.4, *documentation* and *interview* were adopted as sources of evidence in this research. The following sections (3.3.1 and 3.3.2) describe the two data sources in more detail.

3.3.1 Description of document analysis

Documentary information is likely to be relevant to every case study topic. This type of information can take many forms such as letters, memoranda, minutes of meetings, diaries, log books and other written reports of events [Yin 2002]. These documents can be part of a company's or design engineer's work practice created independently of the research study or specifically created for the research [Ahmed 2007]. One of the benefits of document analysis is that the data can be collected without the presence of the researcher. Therefore, the researcher has no influence on the content of the documents to be analysed. However, the limitation of documentation is a mismatch between the contexts created to the objective of the study. Thus, systematic searches for relevant documents are important in any data collection plan. If the documents analysed are created independently of the study, the disturbance to the company/design engineer's routine work is minimal. For case studies, the most important use of documents is to corroborate and supplement evidence from other sources, such as interviews and observations. Documents can also be the main source of data, for example the collection of maintenance and service data to determine the reliability of various products and the effects of improvements [Stephenson 1995 in Blessing and Chakrabarti 2009]. Analysis of documents using techniques such as natural language tools can reveal the reasoning of the design engineers. Consequently, it is a suitable approach when a research aims to capture implicit knowledge about the process and product. The use of document analysis for Studies 1 and 3 in this research is described in more detail in sections 3.7 and 3.9.

3.3.2 Description of interview

The interview is one of the most important sources of case study information. It is an appropriate method for capturing explicit knowledge. The information collected through interviews relies upon the interviewees' memory and what they can articulate during the interview session. One of the advantages of interviews is that the interviewer can ask the interviewees questions about the information they want to know. However, interviewees may have a biased view of the topic of study and articulate information that they believe the interviewer wants to hear.

Interviews can be categorised as follows: 1) unstructured interview; 2) semi-structured interview; and 3) structured interview. In an unstructured interview, the interviewer simply asks the interviewee questions about the topic. Usually, the interviewer has some knowledge of the domain and therefore structures the questions around specific topics while the interviewee acts as an informant. A semi-structured interview consists of an interviewer asking questions with an agenda in which a set of questions is initially prepared, so the resulting data approaches completeness. A semi-structured interview is also the best way to detect whether interviewees misinterpret the questions, and allows the interviewer to ask follow-up questions in order to clarify the matter. The use of interviews in this research is described in Study 2 (refer to section 3.8).

Table 3.4 Six sources of evidence: strengths and weaknesses [Yin 2002]

Source of Evidence	Strengths	Weaknesses
Documentation	• Stable - can be reviewed repeatedly • Unobstructive - not created as a result of the case study • Exact - contains exact names, references and details of an event • Broad coverage - long span of time, many events and many settings	• Retrievability - can be low • Biased selectivity if collection is incomplete • Reporting bias - reflects (unknown) bias of author • Access - may be deliberately blocked
Archival records	• Same as above for documentation • Precise and qualitative	• Same as above for documentation • Accessibility due to privacy reasons
Interviews	• Targeted - focuses directly on case study topic • Insightful - provides perceived causal inference	• Biased due to poorly constructed questions • Response biased • Inaccuracies due to poor recall • Reflectivity - interviewee says what interviewer wants to hear
Direct observation	• Reality - covers events in real time • Contextual - covers context of events	• Time consuming • Selectivity - unless broad coverage • Reflectivity - event may proceed differently because it is being observed • Cost - hours needed by human observer

Participant observation	• Same as above for direct observation • Insight into interpersonal behaviour and motives	• Same as above for direct observations • Biased due to investigator's manipulation of events
Physical artefact	• Insight into cultural features • Insight into technical operation	• Selectivity • Availability

3.4 Unit of analysis of studies

The *unit of analysis* is a very important component to be decided in the development of the research methodology. This has been stressed by Yin [2002] who comments on the need in case studies to define "the case". The unit of analysis can be an individual, organisation, process, programme, neighbourhood, institution or even an event [Yin 2002]. According to Blessing and Chakrabarti [2009], the units of analysis used in engineering design are manifold and include the design team, requirements, product module, design process, decision-making, human-machine interfaces, information exchange, collaboration, documentation and organisation.

In addition, Blessing and Chakrabarti [2009] define the *unit of analysis* as the main element (entity) of the study about which the researcher wants to obtain information, draw conclusions and make generalisations i.e. the unit on which the analysis focuses. *The product* can be the *unit of analysis* if the researcher aims to identify factors that contribute to its attributes' 'quality' or its attributes' 'reliability'. *The designer* would be the *unit of analysis* if the aim is to draw conclusions about the behaviour between designers, including how they approach a design problem. However, *the design team* would be the *unit of analysis* if the aim is to draw conclusions about the behaviour of design teams, for example the way in which team members collaborate [Blessing and Chakrabarti 2009].

In this research, the *unit of analysis* of Study 1 (see section 3.7 for detail) is *change request reports* because the aim is to draw conclusions about the characteristics of a change in specification and its contributions to Engineering Changes (ECs) during the product development process. In Study 2 (see section 3.8 for detail), the *unit of analysis* is the *design engineer* because the aim is to draw conclusions about the way design engineers undertake the development of a specification. Meanwhile in Study 3 (see section 3.9 for detail), the *unit of analysis* is the *specification document* because the study aims to draw conclusions about the way design engineers clarify the design problem.

3.5 Design Research Methodology (DRM) framework

The overall aim of design research is to make a design more effective and efficient in order to enable the design practice to develop more successful products. Thus, design research has two objectives: 1) the formulation and validation of models and theories about the phenomenon of design with all its facets (people, product, knowledge/methods/tools organisation, micro-economy and macro-economy); and 2) the development and validation of support founded on these models and theories in order to improve the design practice, including education and its outcomes [Blessing and Chakrabarti 2009].

The reasons motivating the development of the Design Research Methodology (DRM) framework are due to a lack of scientific rigour in design research, especially with regard to the application of research methods, the interpretation of findings, the development of support, and the validation and documentation of support [Blessing 2002 in Blessing and Chakrabarti 2009]. As shown in Figure 3.1, this research framework was employed in this study. DRM consists of four stages: Research Clarification (RC), Descriptive Study I (DS I), Prescriptive Study (PS) and Descriptive Study II (DS II). Figure 3.2 illustrates the link between the research planning stage and DS I of the DRM framework.

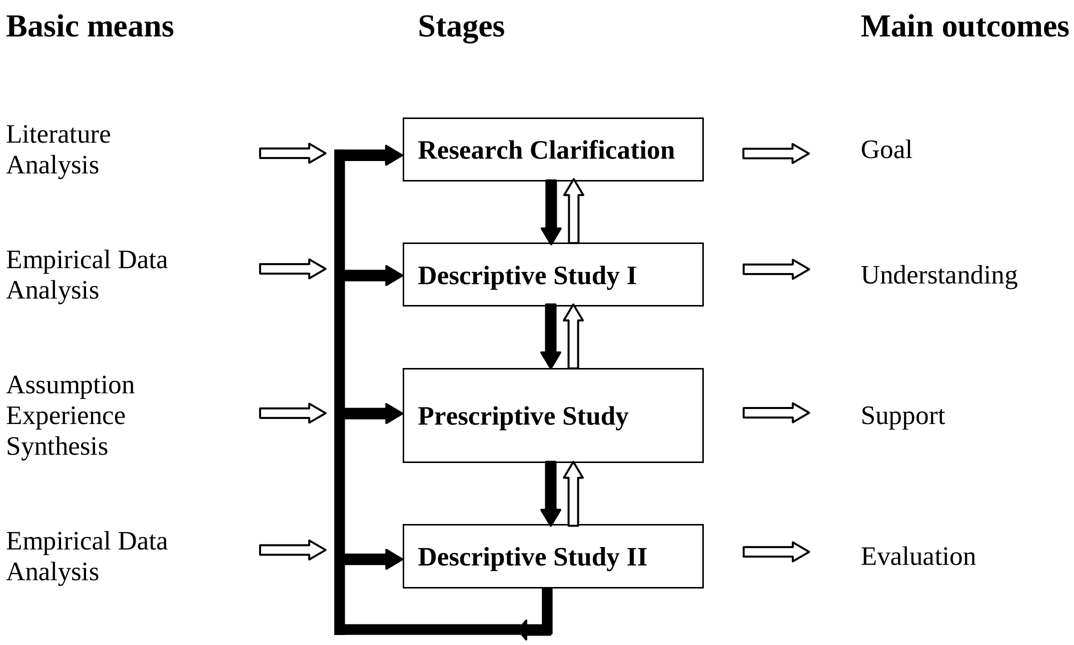


Figure 3.1 DRM framework from Blessing and Chakrabarti [2009]

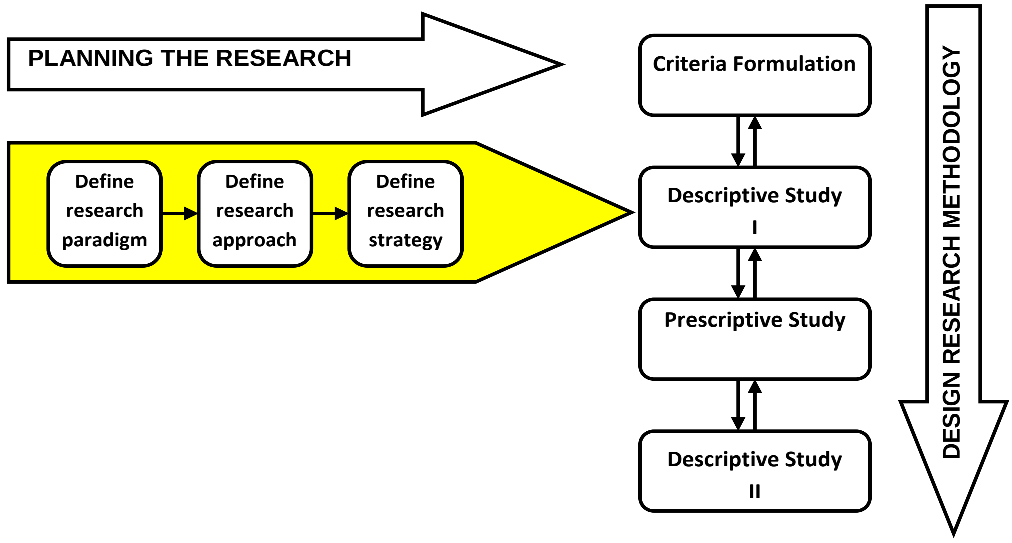


Figure 3.2 Relationship between research planning stage and Design Research Methodology (DRM) framework

In the RC stage, evidence to support the assumption of a design situation within the area of concern is identified. This stage is carried out by reviewing literature related to the three main areas: Design Methodology, Specification and Engineering Changes (ECs) (refer to Chapter 2 for details). The output of this stage was the research questions as introduced in Chapter 1 and restated in Chapter 3 (refer to Table 3.2).

In the DS I stage, the intention is to develop a further understanding of the area of concern and the factors that contribute to its success. Three studies (refer to sections 3.7, 3.8 and 3.9) were carried out at the DS I stage to gain insight into the area of concern. The studies were based on six research questions introduced in Chapter 1. Justification and a sound basis for the development of design support (support to facilitate the task clarification process) are identified through the results of these studies.

In the PS stage, the justification and criteria of support to facilitate the task clarification process are outlined. The development of design support was carried out based on the results of the DS I (refer to Chapter 5).

In the DS II stage, the devised support was evaluated based on the criteria identified in DS I. The evaluation of support was carried out in a controlled experiment with design students. The evaluation was also based on the Kirkpatrick model of evaluation [Ahmed 2000] (refer to Chapter 5 for more details).

3.6 Characteristics of Descriptive Study I (DS I)

A checklist for determining the characteristics of empirical studies was developed by Blessing to support the review of empirical studies in design. The choice of certain characteristics together with the main findings aid in [Blessing 1994 in Blessing and Chakrabarti 2009]:

- Comparing studies, their set up and their findings;
- Formulating justified comments, e.g. regarding the amount of evidence;
- Determining whether pieces of evidence from different studies can be brought together to form strong evidence;
- Finding possible explanations for contradicting evidence; and
- Establishing whether findings can be used as the basis for one's own research, e.g. based on the amount of evidence and the context in which the study took place.

The three studies; 1) document analysis of change request reports, 2) interviews with product development consultants, and 3) document analysis of specification documents carried out in this research project, are mapped onto the selected characteristics (see Table 3.5). In summary:

- The studies were exploratory in nature. The number of documents/participants analysed were not meant for comparison but instead for data enrichment and generality.
- The environment of all studies was industries (real context). The documents were from the aerospace industry and an engineering consultancy firm. The interview participants were all design engineers (product development consultants) in a consultancy firm.

The detailed methods adopted for Study 1, 2 and 3 during the Descriptive Study I stage are discussed in the following sections and an overall summary is shown in Table 3.5.

Table 3.5 Characteristics of descriptive studies (DSI) conducted

Characteristics	Options	Characteristics of studies conducted		
		Study 1 Document analysis	Study 2 Interviews	Study 3 Document analysis
Aim		To understand the significance of changes in specification to Engineering Changes (ECs)	To understand the evolution of requirements during the design processes	To understand the problem with the decomposition process during the task clarification phase
Environment of study	Industry Laboratory	Industry	Industry	Industry
Participant	Number of participants	No	6 design engineers	No
Data collection method	Real time data collection methods, i.e. participant observation, observation, diary-keeping, simultaneous verbalisation, etc. Retrospective data collection methods, i.e. documents,	Document analysis (change request reports)	Semi-structured interviews	Document analysis (specification document)

	product data, questionnaires, interviews			
Data collected	Type of data	Change request reports of a complex product	Audio-recorded	Specification document
	Nature of data	Qualitative	Qualitative	Qualitative
	Size of data	271 reports	6 interviews	3 documents
Duration	Length of process studied	No	45-60 minutes	No
Role of researcher	Contribution of researcher	Absent	Interviewer	Absent
Coding and analysis method	Pre-defined codes Post-defined codes	Pre-defined and post-defined	Pre-defined and post-defined	Pre-defined

3.7 Study 1: Document analysis of change request reports

A document analysis of ECs request reports of an aero-engine was carried out to understand the nature of change in specifications, particularly with regard to its effect on Engineering Changes (ECs) occurrence during the product life cycle phase of an aero-engine. The study aimed to draw conclusions about the characteristics of change in specification and it contributions to Engineering Changes (ECs) during the product development process. This study has two questions: 1) how significant are changes in specification towards Engineering Changes (ECs) that occur during the product's life cycle?, and 2) what can be learnt from changes in specification in order to develop better specification (specification with fewer changes) at the beginning of the product development process?

3.7.1 Choice of document (Case)

An analysis of 271 associated change request reports during an aero-engine's development was carried out. These reports are the subset of 1510 change requests that the product has undergone, encompassing eight years of an aero-engine's life cycle, including two years of the product being in operation at the time of the data analysis. These documents were collected and used by other researchers for different studies [Ahmed and Kanike 2007; Ahmed and Vianello 2011]. In this research context, the researcher reused the available documents to carry out document analysis about changes in specification. Since the researcher did not have direct contact with the company where the documents were produced, information about the context of the documents in design practice was mostly obtained from previous researches. The relevance of the documents (change request reports) to the objective of the study was examined and discussed with the supervisor, who had previously analysed the data, before the analysis began. Since the objective of this study is to draw conclusions about the characteristics of change in specification during the product's life cycle phase, the context in which the reports were produced is relevant to the purpose of this study. The aero-engine was selected for the following reasons:

- The product is complex with several hundred components and interactions between components.
- The product was largely recognised as a success with over 2.3 million flying hours.
- The product is a variant design and succeeds two previous designs.

3.7.2 Characteristics of document

Each report was indexed to 38 true/false statements that described the reasons for change, implications of the change and suggested solutions. In these reports, changes in specification were treated as one of the reasons for changes during the product's life cycle phase. Thus, some of the ECs were not affected in the specification-1239 reports. The reports varied in length from 25 - 250 words and were the first reports that highlighted the need for changes in a product. A change was only documented after the original design task had been completed. These reports originated during the development and prototype phase, manufacture/build and testing phase, and service phase of the engine's life cycle [Ahmed and Kanike 2007]. The reports were created by different people involved in the product lifecycle and were not limited to design engineers. Those involved in the product's manufacturing and service phases also initiated the reports. Reports indexed with a false statement to changes in specifications were excluded from this study.

3.7.3 Data analysis method

In order to quantify several aspects of change in specifications, the following codes were employed and each of the 271 reports was indexed against these codes. These codes were developed based on theory. Each report was carefully examined to understand the reasoning behind the change requests and indexed against pre-defined codes. The indexing process was carried out repetitively until a firm decision was made to index the report to the particular code.

- Initiator for change:
  - *Supplier*: if the change was initiated by the company that supplies components to the producer.
  - *Internal customer*: if the change had a relation to activities undertaken by the company.
  - *External customer*: if the external customer was clearly mentioned in the text and the name of the airline company was mentioned.
- Driver for change:
  - *Error correction*: if the change request was clearly related to a product's deficiency.
  - *Product improvement*: if the change request was not related to a product's deficiency but was aimed at improving an aspect of the product, e.g. to reduce cost.
- Change request description: how the reports were described?
  - *Need statement*: The need is a statement of requirement for a high level description of quality.
  - *Need & Solution*: The need and solution statement is a combination of the need, which is typically stated as a high level description of product quality,

and the solution, which is a proposal by which the means for the need can be satisfied.

  - *Solution*: A solution is stated as an idea to accommodate a certain need or is stated more precisely as the statement of what component/part needs to be changed.
  - *Solution & Consequences*: This statement states the solution in addition to the implication of the change; the benefits if the change is implemented or the drawbacks if the change is ignored.

- Change discovery methods: Data was analysed to identify how change was discovered.
  - *Observation*: an informal method using the knowledge and expertise of the stakeholders.
  - *Assessment*: a formal method through a systematic approach using instruments, software, calculations, etc.

3.8 Study 2: Interviews with design engineers

Semi-structured interviews were carried out to understand the evolution of requirements during the design process including understanding: 1) the development of specification; and 2) changes in requirements during the design process. The study aims to draw conclusions about the way design engineers go about development and manage changes in requirements during the design process. This study has two central questions: 1) how is the development of a specification carried out for a project? and 2) how do specification developers go about formulating requirements for a specification?

3.8.1 Choice of participants for the interviews

The study was carried out in a consultancy company that worked in product development. The consultancy company was selected due to its involvement in the development of different types of products (i.e. mechanical, electronic, electro-mechanical), projects (i.e. product development, design review, etc.), dealing with different types of clients and embarking on different stages of a project. These situations provide a bounty of knowledge to the design engineers in the company, and their experiences were useful for this research. The participants' working experience ranged from 6 to 30 years and the age of participants ranged from 32 to 55 years. Each participant explained a different project that they had been involved with at the consultancy company. Table 3.6 shows the list of participants together with the companies and products that they described during the interview session.

Table 3.6 List of products and clients for each participant in the case study company (B2B is business to business, B2C is business to customer)

Participant	Type of Company	Products	Type of Business
Engineer A	Healthcare company	Medical device	B2C
	Consumer electronic company	Audio visual product	B2C
Engineer B	Consumer electronic company	Audio visual product	B2C
	Research organisation	Sustainable energy equipment	B2B
Engineer C	Valve and fluid handling component manufacturer	Industrial automation product	B2B
	Oil drilling equipment supplier	Mechanism design, mechanical sub-system	B2B
Engineer D	Healthcare consultant	Medical devices	B2C
Engineer E	Healthcare company	Medical devices	B2C
	Service and solution company in security, avionic system	Security system, avionic system	B2B
Engineer F	Valve and fluid handling component manufacturer	Industrial automation product	B2B

3.8.2 Data collection method

Interviews were carried out in the consultancy company based on three themes: 'specification development', 'specification roles' and 'specification changes'. In total, six interviews with six design engineers were carried out. Each participant was contacted through email two weeks before the interview session was scheduled to be carried out. The email requested permission to carry out an interview about the scope of study and also outlined the expected time of the interview session. All the design engineers contacted were willing to be interviewed according to their availability.

Permission to record the interview was requested before the interview session started, and all participants allowed their session to be audio recorded. Each interview lasted for about 45 to 60 minutes and was audio recorded. The interviews were transcribed verbatim and for each interview, 6 to 8 hours were spent on the transcription process. The interviews were semi-structured; the participants were asked about the topic based on a list of questions prepared in advance. Clarification of the questions was carried out when necessary i.e. upon the participants' request. The participants gave their responses to the questions. However, they were allowed to expand the discussion within the scope of the topic with regard to the design itself to provide some examples for their answers. There were also situations where the questions were rephrased into directive questions instead of the original open-ended questions. For example, the question *"How does a design project begin?"* was rephrased for clarity into the more directive question, *"How does a client approach your company for a design project?"* To ensure the participants described information in practice instead of describing what they knew about the topic, they were reminded to refer to the examples and contexts in which the information articulated was employed.

3.8.3 Data analysis method

The interview transcriptions were indexed against a pre-defined coding scheme. The coding scheme was developed based on theory. However, this was expanded upon with codes that emerged during the analysis process. The transcription was parsed into small units called segments. The purpose of segmentation was to facilitate the analysis because the pre-defined code applied only to a single segment. In total, the transcription was divided into 640 segments with each segment varying in length from 1 to 20 words. The results of the analysis were mainly qualitative, and quantitative values were used as an indicator of occurrence. Qualitative analysis was carried out through thorough examination of texts and analysis of the relationships between quantitative results. Some of the predefined coding adopted in this research, together with the definitions and references, are shown in Table 3.7.

Table 3.7 Coding scheme for Study 2

Categories	Codes (Sub-codes)		Explanation	References
Factors that influence the specification development process	Company	The company type	Size, technology, value chain position, etc.	[Darlington and Culley 2004]
		Allocation (budget, time)	Low role or high role	Emerged from data
		Working culture	Top-down, self-growing team, control culture	Emerged from data
		Education background	Academic, practical, method oriented	Emerged from data
		Company-client relationship	Client specification, company specification, cooperation	[Darlington and Culley 2004]
		User of the specification	Synthesis, evaluation, decision, etc.	Emerged from data
	Product	Type of product development	e.g. Technology pull, technology push, platform products, customized product, etc.	[Ulrich and Eppinger 2000] [Darlington and Culley 2004]
		Product's target	Lead time, cost, quality	Emerged from data
		Product's complexity	High, medium, low, system, component	[Darlington and Culley 2004]
	Project	Project phase	The actual stage of the project in which the specification was analysed	[Darlington and Culley 2004]
Aspects considered to lead to identificatio n of requirements	Function		What the product would be able to do	[Pugh 1997]
	Performance		The capacity of the product	[Pugh 1997]
	Material		Type of material to be used for the product/component	[Pugh 1997] [Chakrabarti *et al.* 2004]
	Geometry		The size and form of the product/component	[Pugh 1997] [Chakrabarti *et al.* 2004]
	Option for solution (Improvement)		Available options for improving the product within the requirements	[Pugh 1997]

	Standard	Specific standard or rule that needs to be fulfilled	[Pugh 1997]
	Safety	Safety to the user, standard, test, etc.	[Pugh 1997] [Chakrabarti *et al.* 2004]
	Cost	Total product cost, project cost, cost demand	[Pugh 1997] [Chakrabarti *et al.* 2004]
	Maintenance	How easily the product could be maintained	[Pugh 1997] [Chakrabarti *et al.* 2004]
	Mechanical properties	Strength, deformation, etc.	[Pugh 1997]
	Testing	The kind of testing the product/component needs to undergo	[Pugh 1997]
	Component interface	Interface specs, standard, type	[Pugh 1997]
	Production	Production requirement, cost, technology, supplier, assembly lead time, automation	[Pugh 1997] [Chakrabarti *et al.* 2004]
	Assembly	Manual, automation, volume, etc.	[Pugh 1997] [Chakrabarti *et al.* 2004]
	User interface (Ergonomic)	Safety, easy to learn, easy to use, etc.	[Pugh 1997] [Chakrabarti *et al.* 2004]
	Usage (user, application)	Operator, maintenance personnel, operation hour, etc.	[Pugh 1997] [Chakrabarti *et al.* 2004]

Change initiator	Internal stakeholders		Production team, marketing team, quality team, design team, etc.	Emerged from data
	External stakeholders		Client, regulation bodies, etc.	Emerged from data
Discovery methods for a need to change	Design activity	Problem analysis	Functional decomposition, imposing constraint, criteria set up, requirement rationale, etc.	Emerged from data
		Evaluation of on-going solution	Calculation, simulation, prototype, solution rationale, etc.	Emerged from data
	External factors	Technology driven	Mechanical, software, electronic, material.	Fricke *et al.* [2000]
		Market driven	Economy situation, political issue, environment.	Fricke *et al.* [2000]
		Client driven	Client’s needs	Fricke *et al.* [2000]
Change decision factor	The company		Time focus, quality focus, technology focus, etc.	Emerged from data
	Risk		Low risk, high risk, medium risk	Emerged from data
	Market aim		Customized, special target group, mass production	Emerged from data
	Quality		High, moderate, low quality	Emerged from data
	User		Latest technology, user friendly, safety focus, low cost	Emerged from data
	Strategy		Lead time, cost, quality, image	Emerged from data

3.9 Study 3: Document analysis of specification documents

A document analysis of specification documents was carried out to understand the problem decomposition process during the task clarification phase. This understanding encompasses: 1) the criteria of a specification, 2) the breakdown of issues that form part of the specification and, 3) the relationship between issues and requirements. The study aims to draw conclusions about the way design engineers clarify the design problem during the task clarification phase. This study has two research questions: 1) what do design engineers do to understand the design problem at the beginning of the product development process?, and 2) how do design engineers address and translate the design problem as a list of requirements for a project? (Refer table 3.2-questions)

3.9.1 Description of the projects

Project A

In this project, a new *variant* of an aero-engine was developed based on the two existing designs. This variation aimed to fulfil the varying demands of the customers with regard to the *performance* of the aero-engine. The commencement of this project was based upon the previous aero-engine design. Certain changes to the existing engine were necessary in order to increase the *performance* of the new aero-engine. This project was selected because the aero-engine is largely recognised as a successful product with over 2.3 million flying hours. It is also a complex product with several hundred components and interactions between components. Thus, a large number of issues and requirements were expected. The length of the specification is 77 pages.

Project B

This project was to design a sub-assembly of a cooling system. The design was considered an adaptive design as the consultant was assigned to produce creative designs at the functional level. The consultancy company was assigned to develop three variant designs of a cooling system that was small, medium and large in size. At the beginning of this project, the 1st tier client provided the consultant with a specification document and supplementary documents, including the 2nd tier client’s requirements and regulatory guidelines. Based on these documents and meetings with the 1st tier client, a basic specification for this project was developed by the consultancy company. This specification served as the basis for the design process. In this project, two specifications were developed, namely the client's specification and consultant's specification. Both documents were analysed based on the research questions in this study.

Project C

This project was to develop a wind scanner head to be used for two functions: to detect the direction and to measure the strength of the wind. This project aimed to ensure that windmills were located in the correct position and erected at a strategic location in order to maximise the production of electrical energy. The current wind scanner did not fulfil any of these two functions. Therefore, the consultancy company was assigned to modify the existing scanner in order to achieve the product's aim. Through discussions with their client, the consultancy company decided to develop a new attachment to the existing device to satisfy the functions. This project was categorised as an adaptive design.

3.9.2 Choice of documents

The *document analysis* of three specification documents from two different companies in three different projects (Project A, Project B and Project C) was carried out. These specifications were produced in an aero-engine manufacturing company and a consultancy company prior to the development of a new variant of an aero-engine, a cooling cassette and a wind head scanner (see section 3.9.1, Projects A, B and C for a detailed description of the projects). In Project A, the specification document developed by an aero-engine manufacturer was analysed. In Projects B and C, the specification documents developed by the consultancy company were analysed. In addition, an analysis was also conducted on supplementary documents such as memos with concept sketches for Project B and concept sketches for Project C. The main elements of these specifications were requirement statements and issues related to the requirements.

In general, the three documents were developed for three different levels of product complexity: a *high complexity* product (an aero-engine), a *medium complexity* product (cooling cassette) and a *low complexity* product (wind scanner head). The projects targeted two types of design, *variant* (aero-engine) and *adaptive* design (the cooling cassette and the wind scanner head). A summary of these documents is shown in Table 3.8.

Table 3.8 Summary of the documents

No.	Company	Project	Product	Type of Design	Type of Document	No. of Pages
1.	Aero-engine manufacturer	Project A	Aero-engine	Variant design	Specification document	77
2.	Consultancy company	Project B	Cooling cassette	Version design	Specification document	7
		Project C	Wind scanner head	Version design	Specification document	3

3.9.3 Data Analysis Method

The *analysis* process began by identifying the *issues* in the specification documents of each project. This process was carried out by identifying the *main issues* stated in these documents. Then, the breakdown of these issues was traced and indexed against the level. The main issues were indexed as level 1 followed by level 2, level 3 and level 4 for the sub-issues. Figure 3.3 depicts the breakdown and the level of *issues* in the specification documents.

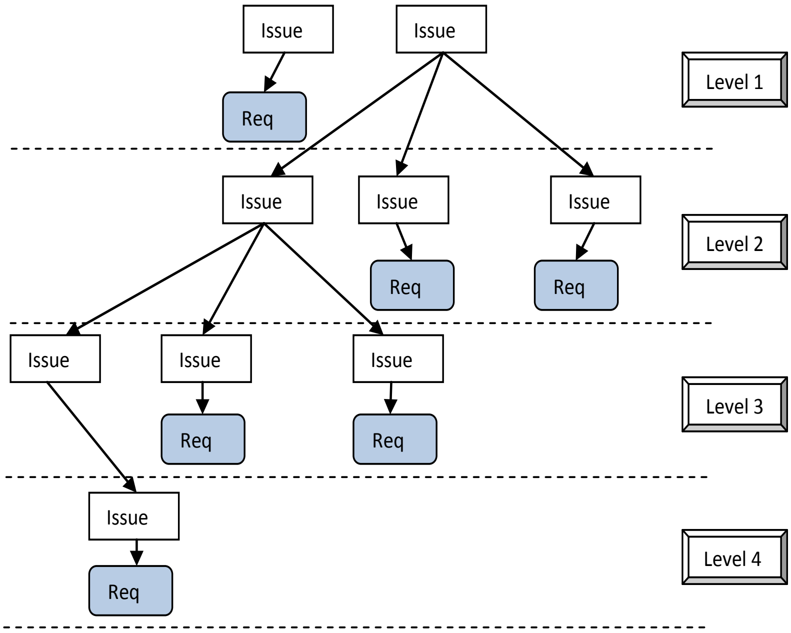


Figure 3.3 Breakdown and transformation of issues into requirements in the specification documents (levels 2, 3 and 4 are sub-issues of the main issues identified in level 1)

To ensure that the stated statement was an *issue*, the following definition was adopted in this study. Prior to the empirical study, it was hypothesised that the *issue* is any consideration made by design engineers in relation to the following [Ahmed 2005]:

- *Functional issue*: required behaviour of Technical Product (TP) under specified condition.
- *Life cycle issue*: attribute of TP required by different life cycle systems.
- *Interface/environmental issue*: attribute of TP required by totality of surrounding condition of its physical environment during the product's life cycle process.
- *Product characteristics*: e.g. structural properties of the product.

Each statement at the specific level of detail was indexed as: an *issue* (1) or as not an *issue* (0). To understand the distribution of these *issues* in the specification documents, the total number of *issues* at the different levels was computed.

In principle, all of these issues were considered as *generic issues*. They may become *specific issues* once specified with the context. The following definition describes the difference between these issues:

- *Generic issue*: an issue without context, e.g. *transportation.*
- *Focused issue*: an issue with context, e.g. *transportation from manufacturer to service centre*.

To determine the number of requirements in the specification documents, each requirement statement was indexed at the different levels of details. The level of each requirement was determined based on its connection to the *level of issue*. For instance, if the requirement appeared after the design engineers considered the *issue* to be at level 1, then the requirement was indexed as a level 1 requirement. If the requirement appeared after the design engineers considered the *issue* to be at level 2, then this requirement was indexed against level 2. The total number of requirements specified in these specification documents was also computed.

3.10 Conclusion

This chapter has described the methodology adopted for this research which was primarily based on the Design Research Methodology (DRM) framework and the specific data collection approaches for the three case studies. All of the stages in the DRM framework were employed in this research though the methodology described in this chapter focuses on the studies carried out in the Descriptive Study I (DS I) stage as described in DRM. A case study approach was adopted for the three studies in the DS I stage. Document analysis and interviews were adopted as the data collection method. All of the methods adopted in this research study were selected after considering the advantages and disadvantages of various methods described in the literature as well as the position of the researcher.

CHAPTER 4: RESULTS OF DESCRIPTIVE STUDIES

This chapter describes the results of three case studies undertaken during the course of this research. The three cases are: 1) document analysis of 271 Engineering Changes (ECs) request reports associated with change in specification once the design process is completed; 2) Six interviews with 6 product development consultants about the evolution of requirement during the design processes and; 3) document analysis of 3 specification documents from 3 different projects within 2 different companies to understand the problem decomposition process during the task clarification phase. The research methodology of these studies is discussed in Chapter 3.

To obtain insight about changes in specification, the document analysis of change request reports was the first study carried out. Since this study covers changes in specification after the design process is completed, an interview was employed to obtain insight about change in requirements during the design process with a focus on the conceptual and embodiment process. The findings of these two studies were motivation for the third study. In the third study, analysis of specification documents was chosen to understand the development of a specification and this study focuses on problem decomposition process which is the transformation of issues into requirement statements. The results of Study 1 provided empirical evidence for Study 2, which then influenced the direction of Study 3.

4.1 Study 1- Document analysis of change request reports for variant design

The document analysis of 271 ECs request reports that are associated to change in specification were carried out. These reports are the subset of 1510 change request reports that the product (aero-engine) has undergone, encompassing eight (8) years of the product's life cycle including two (2) years of the product in operation at the time of study. This study aims to understand the significance of changes in specification to ECs. Each report was indexed against a pre-defined coding scheme (refer to Chapter 3 for further details about the data analysis method). The results presented in this study, are primarily quantitative with an initial qualitative analysis. The findings show that reducing the number of changes in specifications is promising to reduce the number of

ECs during the product’s lifecycle. The focus of the results presented in the next section, are on the following:

- Significance of changes in specifications to ECs, during three different phases of the product’s lifecycle, including understanding the: distribution, driver and design attributes that are frequently requested to be changed (refer to section 4.1.1)
- The initiation of changes in specification including: discovery methods, initiators and choice of ‘statement’ for change requests (refer to section 4.1.2)

4.1.1 Signification of change in specification to ECs

The result of a previous study [Ahmed and Kanike 2007] show that changes in specifications is one of the main causes of ECs during the product’s lifecycle. Thus, the document analysis of ECs request reports carried out aimed to understand how significant change in specifications are as part of all ECs;in the three different phases and all phases of the product’s lifecycle. As shown in Table 4.1, a total of 1510 changes were requested during the product’s lifecycle and 271 of these requests were associated to change in specification. Thus, in overall, change in specification contributed to 18 % of the total ECs during the product’s lifecycle. ECs and change in specification were distributed in three different phases namely; development, manufacture/build & testing and service phase of the product’s lifecycle. The amount of ECs and change in specification at each phase was computed and compared. This comparison aims to understand the significance of change in specification towards ECs during the product’s lifecycle.

During the development phase the amount of ECs requests were 118, 47 of these requests were associated to change in specification. Thus, in the development phase change in specification contributed to 40% of total changes. During the manufacturing/build & testing phase 1147 changes were requested and 192 of these requests were associated to change in specification and represented 17% of the total changes. In the service phase 245 changes were requested and 32 of these requests were associated to change in specification and this contributed to 13% of total ECs. Generally, the contribution of change in specification to ECs ranged from 13% - 40% during the three different phases.

In the change request reports, change in specification was regarded as one of the reasons for changes. Therefore, these results show that change in specification is one of the main causes of ECs at the three different phases and across all phases of the product's lifecycle. It was found that ECs need to be carried out as a result of changes in specification, but not all ECs need change in specification.

The results show that change in specification follows the distribution of ECs during the product's lifecycle. However, direct proportional relationships between these two changes (ECs and change in specification) do not exist. Even though the number of ECs during the service phase was higher than during the development phase, the numbers of changes in specifications at these phases were opposite (see Table 4.1). In addition it was found that, the contribution of change in specification to ECs was only 17% during the manufacture/build & testing phase despite the actual number of ECs being the highest during this phase.

Table 4.1 Distribution of change in specifications and ECs in the product's lifecycle

Lifecycle Phase	**Change in Specification**	**All Changes**	**Percentage of Change in Specification Compare to All Changes**
	No. of Reports	**No. of Reports (Ahmed and Kanike 2007)**	
Development phase	47 (17%)	118 (8%)	40%
Manufacture/build & testing phase	192 (71%)	1147 (76%)	17%
Service phase	32 (12%)	245 (16%)	13%
Total	271 (100%)	1510 (100%)	18%

The underlying motivation (drivers) for a change in specifications during the product's lifecycle was either for *product improvement*: changes that are made to improve the product in response to external factors (i.e. innovation, regulation, etc.) or *error correction*: changes that are made to rectify a product due to a product deficiency.

In general, both drivers; *product improvement* and *error correction* were almost equally important during the product's lifecycle. Figure 4.1 shows the pattern for the drivers of change in specification during the product's lifecycle. It is obvious that *product improvement* is more relevant during the early phases of the product's lifecycle, whereas *error correction* is more relevant during the later phases of the product's lifecycle. An example of changes in specifications due to product improvement was *changing of material in order to gain cost benefit*, and an example of change in specification due to error correction was *redesign of a bracket, as it could not be fitted to the gearbox*. Changes in specification in the two later phases of the product's lifecycle; manufacture/build & testing and service phase was more critical because the tendency of its occurrence due to product errors being higher- 56 % during manufacture/build & testing phase, 69 % during the service phase (refer to Figure 4.1).

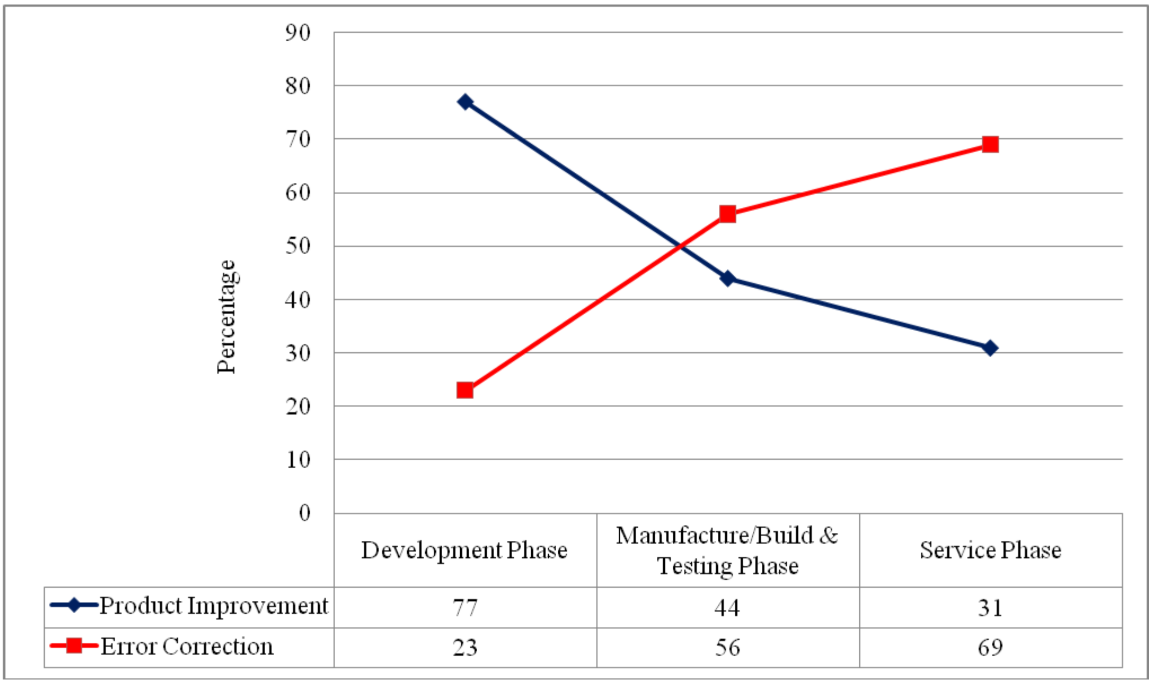


Figure 4.1 Distribution of drivers for changes during the product's lifecycle

The study identified ten different design attributes that were changed during the product's lifecycle, namely; *design parameter, component interface, component, configuration, contract, document/drawing, device setting, software, procedure and protocol*. The three parameters that were most likely to be changed were: *design parameters;* (*i.e., dimensions, shape, tolerances*); *components (i.e., bush, bearing, motor*) and; *documents/drawings*. These results reveal that changes that were carried out during the first two phases of the product's lifecycle (the development and manufacturing/build & testing phase), influenced the physical product itself, whereas changes during the service phase do not change the physical attributes of the product, instead they are likely to change calibration for example.

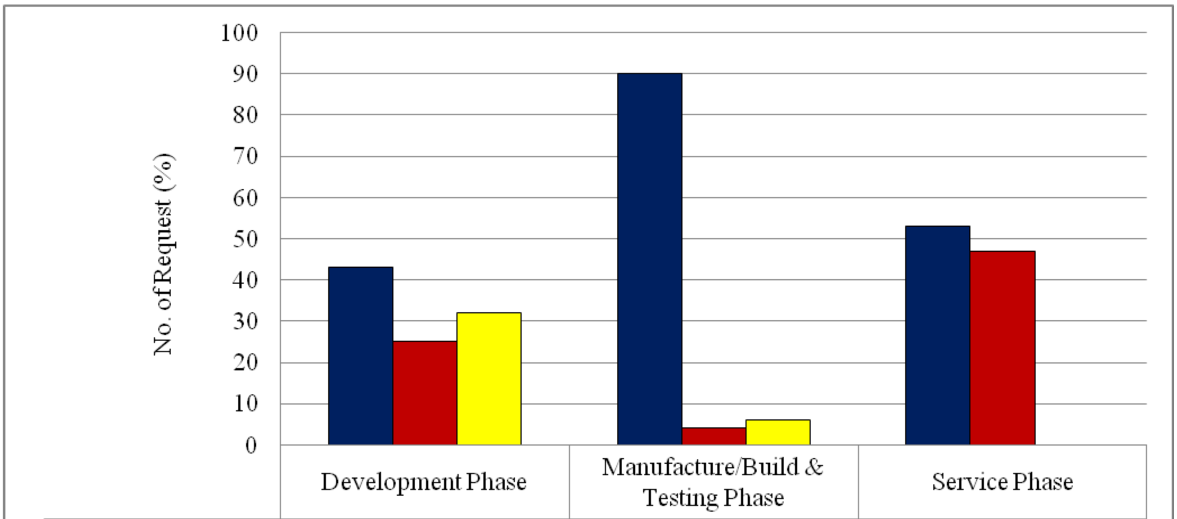
4.1.2 Initiation of change in specification during the product's lifecycle

The reports were analysed to understand the initiation of changes in specification including who initiated a change. A change in specification was initiated by one of the following:

- *Internal customers*: the employees of the aero-engine company (aero-engine manufacturer).
- *External customers*: the customers of the aero-engine company and in this case the airplane manufacturer.
- *Suppliers*: the suppliers of components/sub-systems of the aero-engine company.

Figure 4.2 shows the relationship between the change initiators and the three different phases of the product's lifecycle. Internal customers were the major contributors for the changes initiated during all phases of the product's lifecycle. They contribute approximately to 43%, 90% and 53% of all the changes in specifications during the development phase, the manufacture/build & testing and the service phase, respectively. External customers were active in initiating changes in specification during the development and service phase, and were considered inactive in the manufacture/build & testing phase, even though the amounts of changes were the highest during this phase. Suppliers were more likely to request changes in specifications during the development phase and were inactive during the latter two phases; manufacture/build & testing (only 6 %) and service phase (supplier did not request any changes of specification at the service phase).

On average, an almost balanced distribution of change initiations exist between internal, external and supplier during the development phase. In the manufacture/build & testing phase, the majority of changes were initiated by the internal customer (90%) and while in the service phase, an almost balanced distribution of changes in specification initiations exists between the internal and external customers who contributed to 53% and 47% respectively.



	Development Phase	Manufacture/Build & Testing Phase	Service Phase
Internal Customers	43	90	53
External Customers	25	4	47
Suppliers	32	6	0

Figure 4.2 Initiation of changes in specification during the product's lifecycle

The reports were analysed to identify the ways in which the need for a change was identified. Two methods were employed to discover the necessity for changes during the product's lifecycle phase:

- No method: no formal method, instead reliant upon the knowledge and expertise of the stakeholders
- Formal method: through a systematic approach using instruments, software, calculations, etc.

In general, using *no method* was the main way to discover the need for a change in specification in each phase and also across all phases of the product's lifecycle. However, as the product progresses along the lifecycle phase, the *formal method* became more relevant to discover the need for changes but still less important if compared to using *no method*. This result highlighted that *formal methods* are not entirely successful in discovering the need for all changes and therefore the need for improvement, meanwhile implicit knowledge and experience of change initiators must be captured and transformed into explicit knowledge to improve the change discovery process. Figure 4.3 shows the distribution of the discovery method for changes in specification during the product's lifecycle phase.

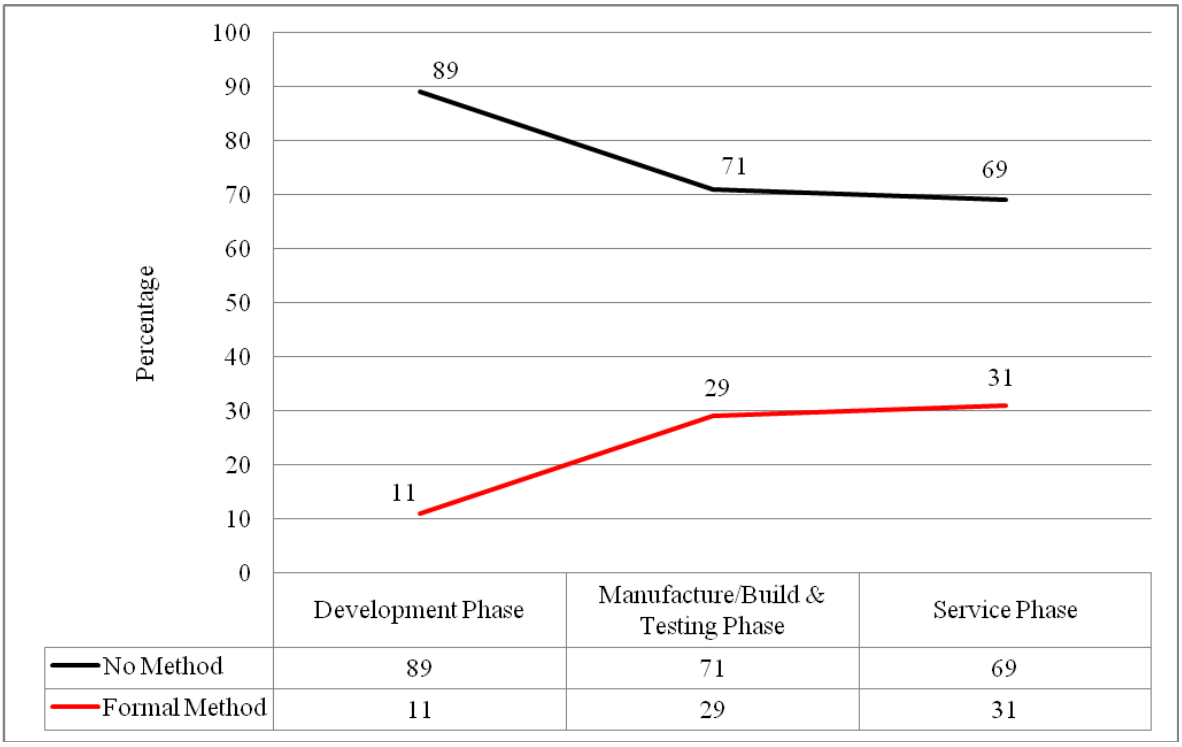


Figure 4.3 Distribution of change discovery methods during the product's lifecycle

The reports were analysed in order to identify the way the reports were described. It was found that change initiators have their own preferred way to describe their requests. The majority of change requests were described in terms of the need & solution statement. The low percentages of reports (at only 4%), which also describe the consequences of a change highlighted the difficulty in understanding the propagation of a change, of one component to another.

4.1.3 Influential factors to changes in specification

From the analysis of the change reports (document study) of an aero-engine, the number of factors that significantly influenced the Engineering Change Management (ECM) process was identified. These factors include initiators, reasons, lifecycle phases, discovery methods and descriptions of change requests. All these factors influence the change request decision, as they feed back to the ECM process. Figure 4.4 shows the factors of a change in specification and its reflection to the ECM process. Deciding how to implement a change immediately or postpone to the next version, the significance of change i.e. if it is or is not mandatory, the implementation process, addressing the change e.g., problem clarification, feasibility study, solutions evaluation, etc., maybe possible if all these factors are known. The right decision is important in order to minimize risk and cost of changes. In designing a good specification, factors such as which of the most frequently changed design attributes are changed, is essentially determined as early as possible. The specification developer has to ensure all design parameters are determined as accurately as possible to avoid over and under design. Thus, correct sizing and choices of components helps to mitigate changes in the latter phases of the product's lifecycle.

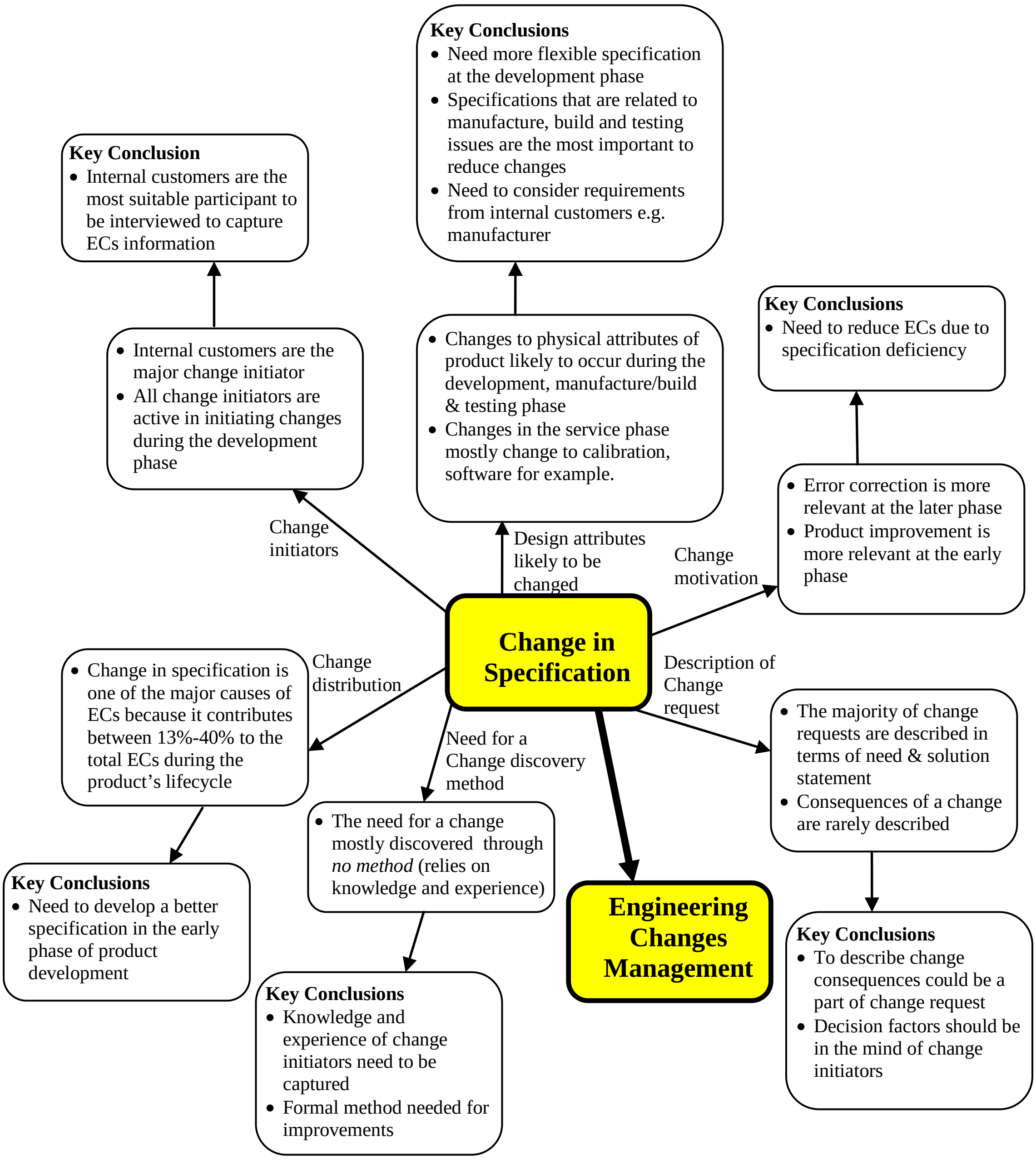


Figure 4.4 Factors that influence a change in specification

4.1.4 Discussion

A study has been carried out to analyse over 271 change reports of an aero-engine during its lifecycle phase that spanned an eight-year period, including two years of the product in service. These reports were the subset of 1500 change request reports during the product's lifecycle. This study aimed to understand the signification of changes in specification to ECs during the product's lifecycle, including understanding: the contribution of changes in specifications, change drivers, request for a change as described, change discovery methods, change initiators and design attributes frequently requested to be changed. In this section the implications of the findings and future direction of work are discussed further.

The lifecycle phases of an aero-engine were divided into development, manufacture/build & testing, and service phases. The study found that changes in specifications to ECs was significantly contributing to 18% of the total changes during the product's lifecycle and contributing to around 13% - 40% of the total changes in each phase. This result shows that change in specification constitutes a normal part of ECs during the product's lifecycle. Since change in specification was regarded as one of the reasons for a change (ECs) any changes in specification will cause ECs (changes to the product). However, not all ECs require a change in specification. All the changes were motivated either for product improvement or error correction. In general, these two motivation factors were equally important (see Figure 4.1). However, error correction is more significant in the later phase whereas product improvement is more significant in the early phases of the product's lifecycle. Error correction which is due to product flaws maybe due to the quality of a specification. However changes in specification for product improvement are difficult to control due to external factors e.g. technology development, material innovation, or new legislation. All these factors may change during the course of product development especially for products with long development cycles. Thus, developing a good specification is essential to ensure changes are not due to specification deficiency and at the same time design engineers must be responsive to external factors that motivate changes.

Even though change in specification can be an advantage, for instance, if it is for product improvement some other changes in specification maybe unnecessary and can be avoided, for example if the changes were due to design flaws as a result of a specification deficiency. An example takes into consideration the amount of change in specification at the manufacture/build & testing phase. Based on this study it was found that 192 changes to specification (refer to Table 4.1) occurred during this phase and 56 % of them (refer to Figure 4.1) were due to error correction. Therefore, around 182 of specification changes at this phase were due to design flaws hence reflect the importance of the accuracy of a specification and can be avoided through development of a good specification at the start of product development. Despite changes in specification for error correction being the highest during the service phase (refer to Figure 4.1) these changes are less critical because most of these changes do not influence the physical attributes of the product. Changes in specification leading to changes to the physical attributes of the product only occur at the development and manufacturing/build & testing phase. This highlighted that specifications that are related to manufacturing/build & testing phase should be given more emphasis during the development of a specification. Inputs from those involved in these phases are valuable for developing better specifications.

As change requests are concentrated during the manufacture/build and testing phase, further investigation of the relationship between them (a change request to another change request) is needed to avoid conflicts between requested changes. However, only 4% of the reports analysed describe possible consequences of the change. Furthermore, would help to avoid the repetition of work as time progresses. The study also found that two main methods were used for discovery of change in specifications namely: *no method* and *formal method* i.e. through knowledge and experience rather than a formal method. However, the majority of changes in specifications were discovered through *no method*. To ensure ECs can be discovered as early as possible, assigning the right person, to the right task, at the right time, during the planning phase is vital or improving the *formal methods* to assess changes needs to take place. This finding also highlights the importance of individual knowledge and expertise to discover the need for changes. Thus, understanding the implicit knowledge of experienced engineers to discover changes through informal methods could be investigated and transformed into explicit knowledge is possible. This information is essential for knowledge sharing and knowledge transfer amongst engineers in the organization, across the project, function and product. Early discovery of changes will significantly reduce the implication of changes, in terms of cost and effort.

The need for change is usually discovered during the integration and testing of parts and systems [Clarkson *et al.* 2001]. In the manufacture/build and testing phase, the components or sub-systems were subjected to physical testing, manufacture and assembly. These activities may reveal any deficiency of the product, leading to the change in specification requests. The deficiency of the product is termed as an emergent change, with a need for correction [Clarkson *et al.* 2001]. The study found that error correction is the primary driver for change in specifications in the manufacture/build and testing phase and during the product's lifecycle. Error correction contributes to around 56% of the change in specifications during the manufacture/build and testing phase. Changes that are due to product improvement are likely to be earlier in the product's lifecycle but their costs are only justified later in the lifecycle. In the case of variant design, as is the case of this study, the start of the design is based upon the latest variant of the product. Any deficiencies that were observed on the latest variant provide valuable input for the next product. Feedback from the latest variant design to the new design is treated as product improvement. This feedback is always incorporated during the development phase. Changes for product improvement are less relevant as the product progresses along the lifecycle phase, due to costs involved.

During the product lifecycle, the study found that change in specifications initiation was always described in terms of need and solution. However, each of the change initiators has their own preference in describing change requests. The study reveals that the internal customers preferred to describe change requests in the solution and need statement. Meanwhile, the external customers and suppliers preferred to describe the change requests in the need statement. The internal customers are company employees who have their own specialty and function; hence, it is not surprising that they prefer to describe their change requests in the solution statement, since they are most likely to know how to fix these problems. To satisfy a change request, engineering designers are required to find a low impact solution. However, if the solution from the initiator of change is always accepted, then the change process must be managed in an efficient way, for cost and time minimization. Therefore, further investigation of changes due to design error and detail classification, is essential to ensure proper production planning prior to production. Proper planning of production enables companies to reduce the impact of a change to the whole production capacity. However, the majority of change initiators are not aware of the consequences of a change at the time they request a change. Hence, balanced consideration between the risks and benefits of a change is essential in any change decision.

The research reveals that the suppliers were most likely to request a change during the development phase and they did not request any changes during the service phase. This highlights the importance of involvement of suppliers in the earlier phases of the product's lifecycle to define specifications. The study also highlights that changes are most likely to be discovered by internal customers. This result is in agreement with findings by [Ahmed and Kanike 2007]. They found that externally initiated changes are more likely to take place during the earlier phases of the product's lifecycle i.e. the originator of the change was a customer, supplier or contractor. This highlights the importance of clients and suppliers needs to modify specifications. Since the reports during the product's service phase are represented around two years, the suppliers may still request changes, as the products service is not completed.

The results of the study also revealed that the three designs attributes, which are likely to be changed during the product's lifecycle are the design parameter, component and document/drawing. This highlights the importance for engineers to consider interface, component and design parameter, in designing a complex product such as an aero-engine, and their relationship. An understanding of their dependency and their function, through approaches, such as a Design Structure Matrix, may help address the knowledge of interfaces and may help to reduce the number of changes during the product's lifecycle [Steward 1981].

4.1.5 Conclusions

A study has been carried out to analyse a complex product's lifecycle, focusing on 271 reports (from 1510 reports) on change in specification. The approach adopted was to conduct a deep analysis of one case to understand change in specifications. From the document analysis, it was found that change in specifications is one of the main causes of ECs during the product's lifecycle. ECs can be reduced by reducing the number of changes to specification and through developing a better specification at the beginning the design process. Developing a more flexible specification at the development phase, taking into consideration issues related to manufacture, build and testing phase and considers requirements of internal customers e.g. manufacturer, are among the necessary steps to producing a better specification.

Knowledge and experience is essential to discover the need for changes as *formal methods* are less effective in discovering changes and therefore need improvement. To capture knowledge about ECs, internal customers are the most important sources of information because they are active in initiating changes in all phases of product's lifecycle.

Several issues have to be considered when designing a specification i.e., the technical content, the role of the specification during the design process, etc. This is to ensure that change in specifications leading to engineering changes due to specification deficiencies are unlikely to occur, particularly in the latter phases of a product's lifecycle. Therefore, it would be beneficial to design a specification, bearing in mind that changes are likely to occur. Understanding the factors, which contribute to change in specifications, provides a good basis for change decisions. These factors could be presented to the change board for their consideration. This research has investigated the significance of change in specification to ECs during the product lifecycle phase and identified factors that influence the specification development. This is a starting point to understand how to achieve a specification with minimum changes, in particular those that are late in the product's lifecycle and are particularly costly.

4.2 Study 2- Evolution of requirements during the design process for new product version

From the results of study 1 it can be concluded that, developing a better specification at the beginning of the design process is significant to mitigate ECs that are due to specification deficiencies. Thus, interviews that are carried out aim to understand the evolution of specification and management of changes in requirements during the product development process which was undertaken in a consultancy company. The knowledge and experience of design engineers in carrying out the specification development process was captured through six (6) interviews with six (6) product development consultants (design engineers). The summary of the product, type of company and type of business that the participants described during the interview session is summarised in section 3.8.1 in Table 3.6. The interviews were audio recorded and transcribed. The qualitative data was analysed based on a pre-defined coding scheme. The codes were expanded as new codes were identified during the course of analysis (refer to Chapter 3 for detail description of the data analysis method). The study results presented in this section are divided into two themes:

- The development of specification; specification development and influencing factors for specification development (refer to section 4.2.1), aspects and sources of requirements (refer to section 4.2.2) and roles of specification (refer to section 4.2.3).
- Changes in requirement; initiation of changes (refer to section 4.2.5), discovery of need for changes (refer to section 4.2.6) and factors and decision for requirement changes (refer to section 4.2.7),

The number of instances (number of mentions) of each observational unit is presented in the results.

4.2.1 The development of a full specification

The interviews revealed that product development consultants received various states of specification from their clients at the beginning of a collaboration project. They received the specification in one of three different states; these were (see Table 4.2):

- Verbal (non-written) specification received- the client approaches the product development consultant with a basic product idea and only verbal requirements about the product are available.
- Semi-developed i.e. only partially written down and finished- the client approaches the product development consultant with a clear product idea and a semi-developed specification of the product is available. Further effort is required to develop the full specification.
- Full specification document (fully written specification and finished)- the client approaches the product development consultant with a fully developed product idea that they want, and thus, the client provides the full specification to the consultant and no further specification development is required.

This result is in agreement with the finding of Darlington and Culley [Darlington and Culley 2004]. In addition the study found that, the product development consultant received a semi-developed specification from their client at the beginning of the collaboration project, for the majority of cases as shown in Table 4.2.

Table 4.2 Types of client's specification

Type of Specification	Verbal	Semi-developed	Full specification
No. of Instances	2	11	2

Further development of an initial specification to full specification is carried out if the clients provided only a verbal or semi- developed specification. A design engineer in the consultancy company, rather than the client, was always responsible to develop the full specification for a project.

Clients sometimes provide full specification to the consultancy company. This has been mentioned by participants of the interviews. In this case, design engineers were requested to rectify flaws of an existing product without need to change any requirements in a client's specification e.g. *meeting the specific requirement in the specification.* Despite these cases where the full specification was developed by the collaboration of both consultant and client, the result highlighted that design engineers need to spend a large amount of their time to develop the specification in the early phase of the product development process. Design engineers in the consultancy company should bear in mind that developing the full specification is one of their tasks.

The development of the full specification generally started prior to the start of the design process which is the ideal situation as proposed in design methodology literature [Ulrich and Eppinger 2000; Pugh 1997; Ulrich and Eppinger 2000]. This specification is still subjected to changes during the course of the design process.

The specification developer e.g. design engineers, in the consultancy company develops the full specification under several influencing factors. These factors (refer to Table 4.3) are:

- *Company*: The company type, budget allocation, working culture, education background, the user of the specification and company-client relationship.
- *Product*: Complexity of the product, product's target and types of product development.
- *Project*: Project phase.

(Details description of these categories can be found in the coding scheme in Chapter 3 section 3.8.3)

The company factor included; budget allocation for a project, the working culture in the company, the education background of the design engineers, the user of the specification and company-client relationship (i.e. in business-to-business context), were a great influence to the development of a specification as shown in Table 4.3. Similar results of factors influencing design requirement were also found in another study i.e. company type, stakeholders relationship, product type and product complexity [Darlington and Culley 2004].

Table 4.3 Factors that influence the development process of the Full Specification

No.	Factor	Sub-Factor	No. of Instances
1.	Company	Budget allocation	14
		Working culture	
		Education background	
		User of the specification	
		Company-client relationship	
2.	Product	Complexity of the product	6
		Product's target	
		Types of product development	
3.	Project	Project phase	1

Figure 4.5 illustrates how the company plays a central role in the specification development process. The company may engage from the start of a project or become involved in the later phase of product development project. The products were differentiated based on the type and complexity. These two factors: project and product are directly influenced by the company and will affect the specification development process. The company also have employees with their own education background that influence the working culture in the company. In addition, the allocated budget for a project and the product target i.e. when it should be released to the market, influence the specification developer in developing a specification for a project i.e. how much time they have before the deadline. Also, the user of the specification and company-client relationship influence the specification.

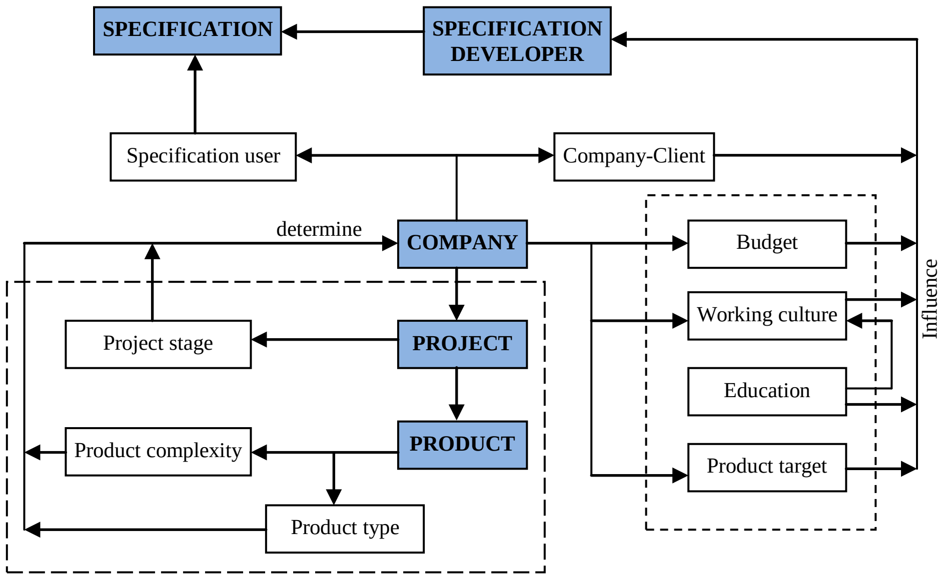


Figure 4.5 Relationship between factors and sub factors influencing the design of the Specification

4.2.2 Identification of sources and aspects of requirements

The interviews were analysed to identify the sources of a requirement and aspects that design engineers consider while formulating a requirement. Aspects are the matters that design engineers consider to formulate a requirement i.e. *standard, material, testing.* Designer engineers were found to have considered 17 aspects related to the product during formulating requirements in a specification (refer Figure 4.6). The 17 aspects considered were: *usage, user interface, assembly, mechanism, production, component interface, testing, mechanical properties, maintenance, cost, safety and standard, option for solution, geometry, material, performance and function.* The majority of the requirements were identified when the design engineers considered the user of the product being designed and its related aspects including; usage (i.e. application, user), user interface (ergonomic) and safety.

Two approaches to searching for requirements were observed during the course of the design process, these were:

- Aspect *i.e. safety, maintenance* to source
- Source to aspect.

These approaches occurred in both the problem and solution domain, *e.g. the specification developers begins by considering the safety aspect then they identify the end user as the source. Furthermore, they start with the end user and start to consider ergonomic aspect.* Figure 4.7 shows the approach to searching for requirements during the design process for a project.

This result has highlighted the importance of communication and knowledge sharing between design engineers with other stakeholders in order to develop a good specification. Furthermore, by considering all the aspects and sources (origin) of requirements continually along the design process, may result in a reduction in the number of changes in requirement.

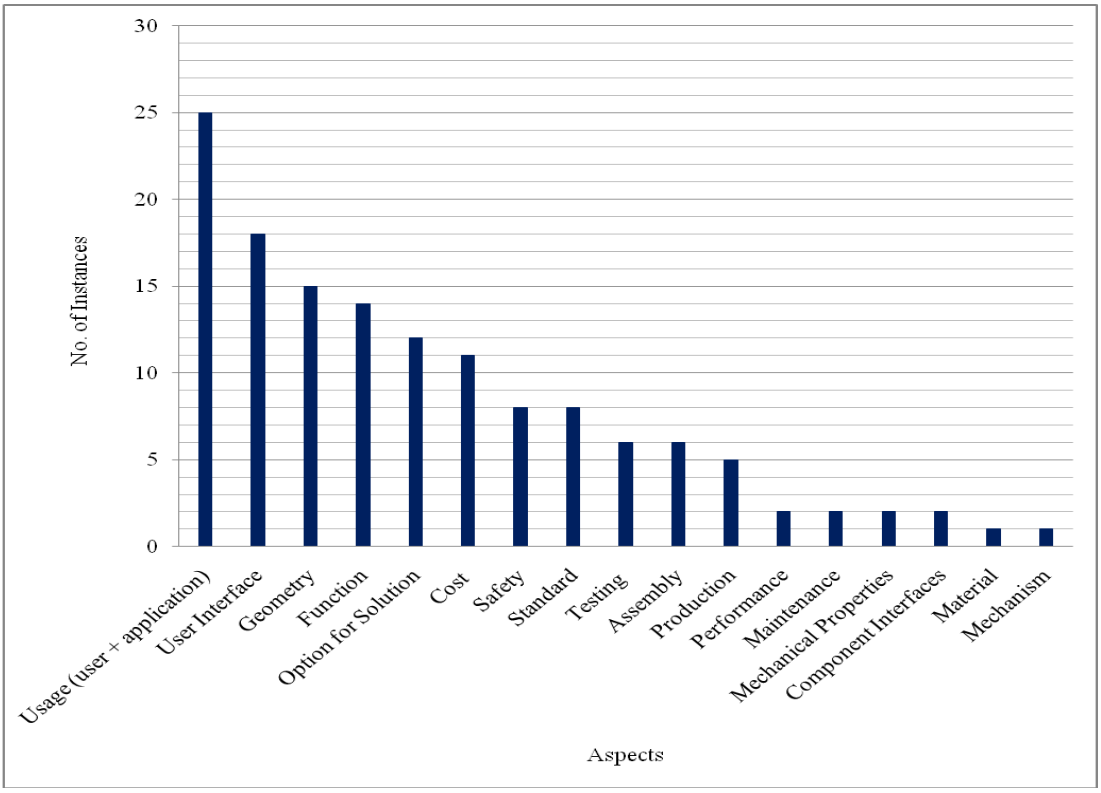


Figure 4.6 Aspects considered leading to identification of requirement

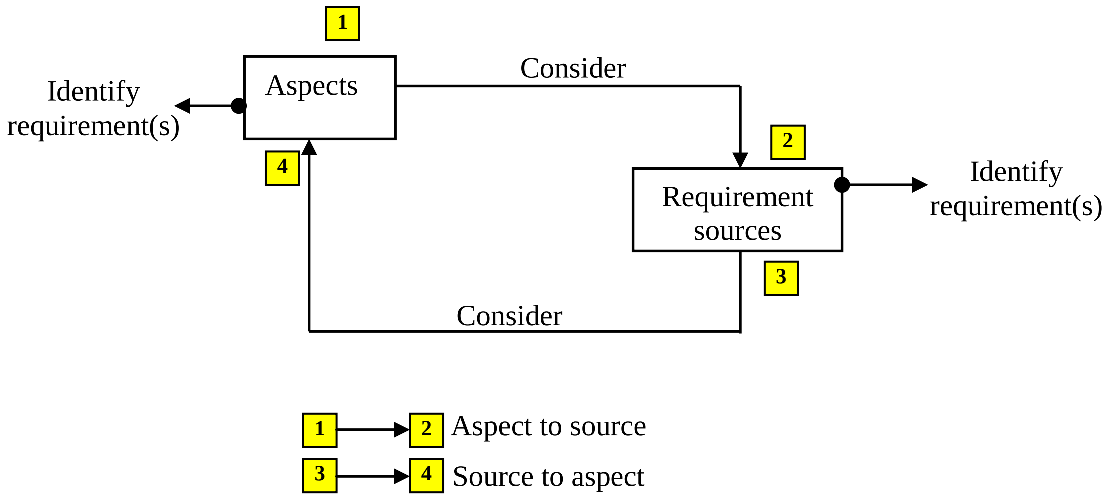


Figure 4.7 Approach to searching for requirements for a project

The study found that the requirement sources were either from:

- *Human*: Client, end user, market analysis report, colleagues, the designers' expected solution, designer's own requirement.
- *Artefact*: Semi-developed specification, proposed solution, existing product, previous project, design guideline, user guidelines.

The major sources of requirements during the design process were human sources as shown in Table 4.4. Design engineers preferred to consult their colleagues to obtain information about requirements. The study of [Romer *et al.* 2001] and [Wootton *et al.* 1997] also discovered similar results about the sources of requirements i.e. colleagues, customer, document, other departments (i.e. sales department, marketing and manufacturing) [Romer *et al.* 2001] and customer, user, supplier, written material (i.e. book, trade journal, technical manual) [Wootton *et al.* 1997].

Table 4.4 Sources of requirements during the design process

No.	Source of Requirement	Sub-Source of Requirement	No. of Instances	Total Instances
1.	Human	Client	6	31
		End user	4	
		Marketing	2	
		Colleagues	11	
		Expected solution	3	
		Designer's own requirement	5	
2.	Artefact	Semi-developed specification	1	19
		Proposed Solution	5	
		Existing product (prototype, previous product)	8	
		Previous project	3	
		Design guidelines	1	
		User Guidelines	1	

4.2.3 Roles of specification during the product development process

The specification plays a vital role in the product development process and was found to have various roles including (see Figure 4.8):

- Guidance to designers: design engineers always refer to the specification as to ensure they are still working within the design space as stated in the specification.
- Identify trade-off between requirements: the specification is the written document that is used for trade-offs between requirements during the course of designing.
- A checklist e.g. during milestone: meeting-identify which requirements need to be established, already established, and are not possible to be established.

- Evaluation of solutions to select the one that is most suited to the specification- several requirements that differentiate a solution and criteria for a good solution is always referred to throughout the design process.
- An agreement within the design team, and an agreement with the client e.g. company-supplier agreement on fulfilling the design task
- To trace the likelihood of change propagation by considering the objective of each requirement as these requirements may have a shared objective (e.g. for safety concern) that could depend on other requirements. Thus, design engineers continually consider these types of requirements during the course of designing especially when it involves changes to a requirement.
- Product overview-based on the list of requirements in the specification, design engineers generate the imaginary solution of the product and this solution is always sketched for concept suggestion that they will always discuss with their client.

Figure 4.8 shows the roles of specification for a project and the number of instances for each role. The specification was frequently used to guide the design engineers to search for feasible solutions. This result is supported by the finding of a previous case study [Romer *et al.* 2001]. They found 84% of the interviewees reported analysing the requirement before developing a solution. Similar roles i.e. guidance, verifying solutions and reaching an agreement was also found in a previous study [Nijhuis and Roozenburg 1997].

This result highlighted some important notes. Firstly, the developers of specification should be aware of the roles of specification as it is being designed to ensure that it is useful and of benefit to design engineers to execute their design tasks. Secondly, further research to characterise specification based on it usages is essential as the specification has multiple roles in the product development activities to that described in design literatures.

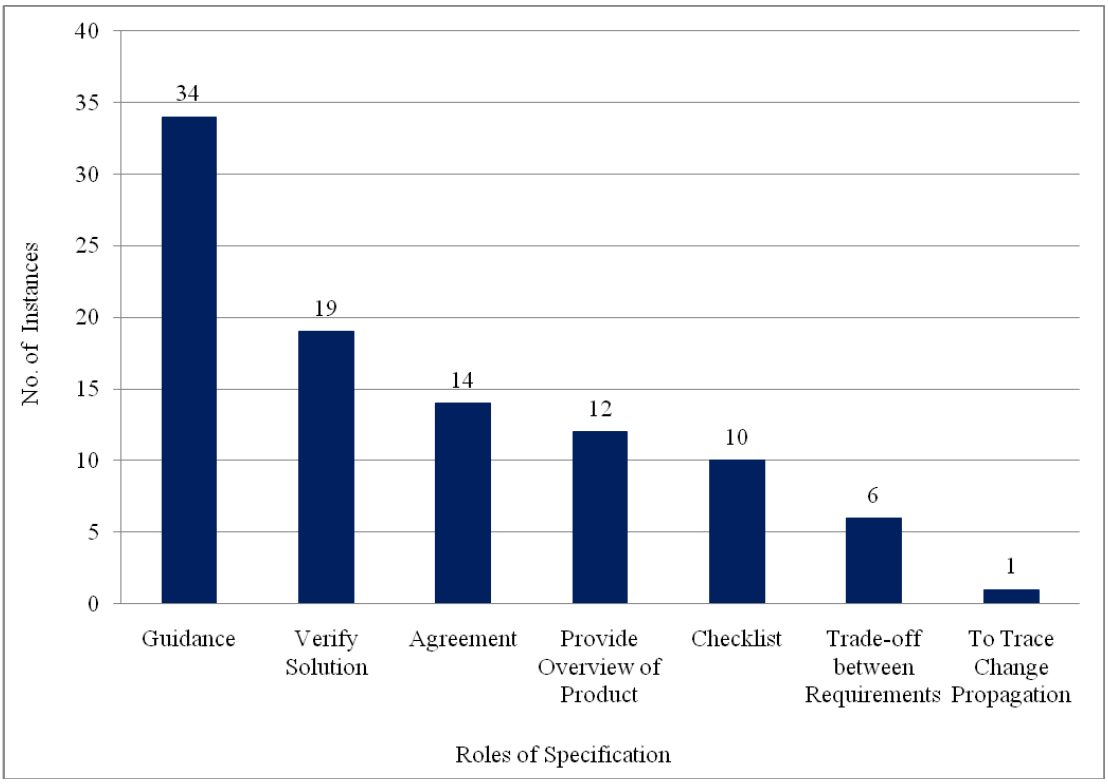


Figure 4.8 Roles of specification during the product development process

4.2.4 Model of design information flow in collaboration project

The illustration of the information flow from client to design engineers in the collaboration project is shown in Figure 4.9. Each of the steps, 1 to 9 is described here.

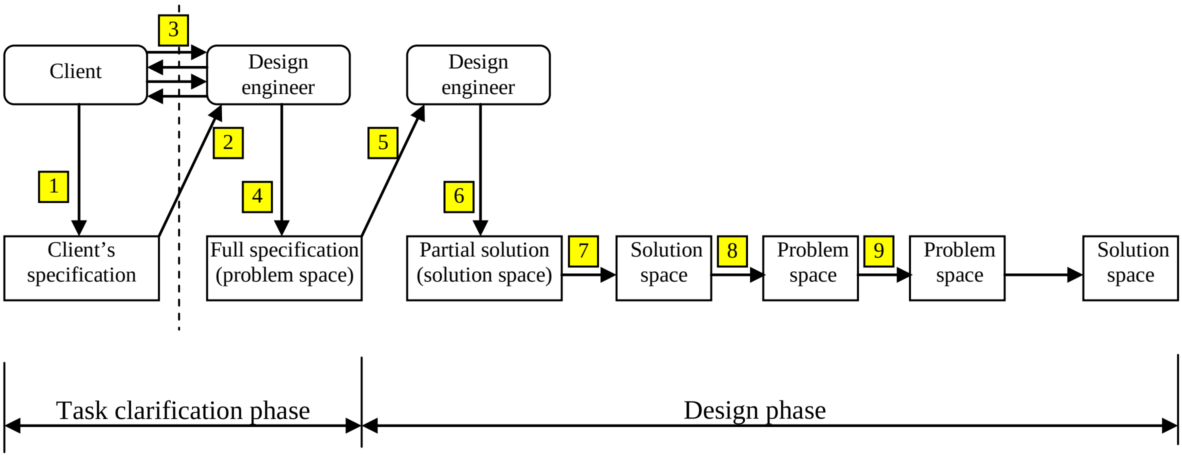


Figure 4.9 Model of the information flows in the case study company

1 Clients prepare their own specification at different levels of detail. In general the client's specification can be divided into three categories: verbal, semi-developed and full specification.

2 Client approaches company with their specification; verbal, semi-developed or full specification.

3 A lot of discussion takes place between the client and designer to clarify the requirements until mutual agreement is achieved.

4 A design engineer starts to develop full specification based on the mutual agreement.

5 Once the full specification is considered complete, it will be distributed to design engineers in the project team.

6 Design engineer start to develop partial solution of the design problem.

7 Design engineer continually develops partial solutions in more detail based on the early formulated problem.

8 Design engineer shifts from the solution space to the problem space through solution evaluation process.

9 Design engineer remains in the problem space and discovers new requirements through problem analysis process.

4.2.5 Initiation of change in requirements

The interviews were analysed to understand the process of initiating changes in requirement during the design process. Changes in requirements were initiated either by:

- *Internal stakeholder*: i.e. design engineers within or outside of the project team.
- *External stakeholder*: i.e. the client (production engineers, marketing or quality engineers in the client's company).

The results show a balanced distribution of change initiations during the design process between the internal and external stakeholders, as shown in Table 4.9. However, the interpretation of the results is influenced by the set-up of the companies, for instance, in the context of a manufacturing company, the *internal stakeholders* (including production engineers, quality engineers, marketing personnel) maybe seen as *external stakeholder* from the consultants' viewpoint.

In practice, the involvement of external stakeholders during the early phases of the design process was considerably active and should be encouraged as early as possible i.e. during the specifications development. This is to ensure that more requirements may be identified, for instance, requirements regarding the stakeholders' needs. The study found the input from the client is received mainly during meetings with the client.

Two approaches were adopted for change in requirement requests either a top-down approach or bottom-up approach. These approaches are closely related to the reason for changes. In many situations top-down approaches were due to economic reason (to find the most economical solution) whereas bottom-up approaches were mainly due to technical reasons (to find the most feasible solution).

Table 4.5 Initiation of change in requirements

Changes Initiator	**Internal Stakeholder**	**External Stakeholder**
No. of Instances	12	10

4.2.6 Change discovery during the design process

The study found that two design tasks contributed to discover the need for changes were:

- *Analysis of problem*: i.e. functional decomposition, imposing constraint, criteria set-up, requirement rationale, etc.
- *Evaluation of on-going solution*: i.e. calculation, simulation, prototype, solution rationale, etc.

An almost balanced contribution between these tasks was found when discovering the need for changes during the design process. *Analysis of problem* always resulted in requirement changes and somehow led to a more concrete requirement. A separate study, [Romer *et al.* 2001] found that 84% of the design engineers analysed the requirements before developing solutions, whereas the remaining 16% began with solution development and subsequently deduced the requirements of the product. Meanwhile, the evaluation of on-going solutions was carried out by considering if the written requirement was true and needed to be fulfilled - for instance, a requirement for *standards* and *safety,* which is a mandatory fulfilment. This result highlighted an essential need for design support to assist design engineers in problem analysis during the early phases of the design process.

Two major flaws of requirement identified were; over specified and not specified. Under and over specified requirements may lead to under and over designed product, respectively. On the other hand, the not specified requirements may lead to not fulfilling the stakeholders' needs. However, amongst these flaws, incorrect requirements can be most dangerous as it may lead to the product failing in the market and resulting in the products inability to solve the intended problem, as required by the stakeholders. Thus, avoiding this flaw is more essential than the others are. This result highlighted the difficulty to estimate the exact value of design parameters early in the design process.

The understanding of the change requests flow was also a part of this research. However, it was difficult to identify the flow of change requests as changes during the design process were informal and lacked a standard procedure. During the design process changes in requirements occur in both directions: 1) a direct request- change in requirement was directly requested by initiator, leading to solution changes; and 2) an indirect request-change in solution was requested leading to requirement changes. The flows of change requests are shown in Figure 4.10.

In the situation where design engineers identify that is a necessity to change the requirements due to its flaws (justification of requirement flaws was made based on knowledge and experience of design engineer, which was discovered during the problem analysis), a direct request is likely to occur. When it was discovered during the evaluation of an on-going solution, then an indirect request was likely to occur.

There was a tendency of the design engineers to change the on-going solution prior to changing the requirement. Changes in requirement occur in both domains (problem and solution) during the design process. These changes were to update requirement lists to become more concrete and also for controlling the direction towards an appropriate design solution. This result also has a relationship to the results from previous studies [Nidarmarthi 1997; Kurukawa 2004] which defines designing as co-evolution between requirements and solution in the problem and solution domain. Analysis of problems occur in the problem domain, meanwhile the evaluation of on-going solution occurs in the solution domain. Figure 4.9 depicts the change in requirements flow during the design process.

Table 4.6 Flow of change in requirement requests

Flow of Request	No. of Instances
Direct Requests	7
Indirect Requests	9

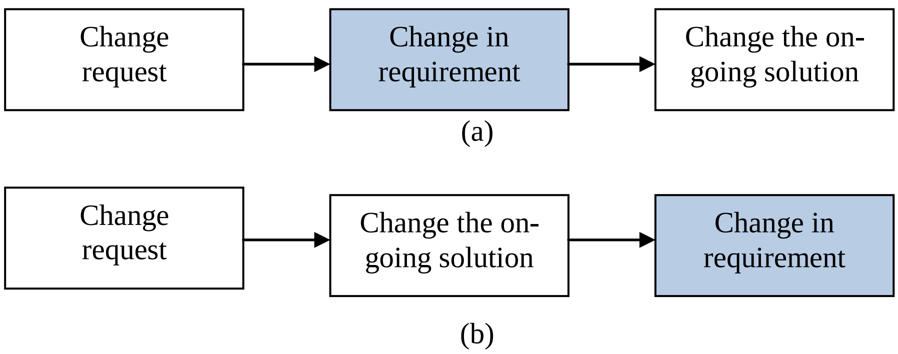


Figure 4.10 Flows of requirement changes for (a) direct requests and (b) indirect requests

4.2.7 Factors and decision for requirement changes

The study found that several external factors (see table 4.11) *i.e.* technology progress, market demands and client demands also influence requirement changes during the course of designing. For instance, the client asks for a requirement change as a result of market expansion or as the latest technology is introduced into the market e.g.

communication technology, manufacturing technology, etc. The results from the study reveal that *market demands* were the primary change factor during the design process. This result highlights the importance of considering the market demand, technology update and client preference throughout the design process. Therefore, design engineers must be responsive to these factors instead of solely focusing on fulfilling the existing requirements.

Table 4.7 Factors for the requirement changes

Factor	**Technology Progress**	**Market Demand**	**Client Demand**
No. of Instances	6	17	2

This study found six factors (see Table 4.12) that influence decisions regarding change in requirement, these were:

- The company: i.e. time pressure and quality focus.
- Risks (potential losses): low risk, high risk or medium risk.
- Market aim: special target group, customized, etc.
- Quality of the product: highest, lowest or moderate quality.
- User expectation: i.e. latest technology, safety, user friendly, low cost, etc.
- Business strategy: i.e. lead time, cost, quality, etc.

Risks (potential losses) of a change were the major factor influencing the change in specification decision during the design process (see Table 4.12). Even though the change in requirement process in the design phase is not formal, for the decision to be made to either change the requirement or not, the decision maker always considers these six factors.

Table 4.8 Factors that influence to change decision

No	Factor	No. of Instances
1	Company	2
2	Risks	13
3	Market aim	2
4	Quality of the product	5
5	User expectation	2
6	Business strategy	7

4.2.8 Descriptive model of changes information flow

Figure 4.11 illustrates the information flow for change in requirements. Even though the change process during the design process lacks formality, implicit procedures still exist. As depicted in Figure 4.11, the implicit process is comprised of; identification of the need for change, change request, change decision and change implementation. In order to make a change decision, it is essential to identify in advance information from the upstream processes (e.g. identify need and change request) and its information content (e.g. factors, type of flaw, flow of request, approach). This information is related to the decision-making factors considered during the decision process.

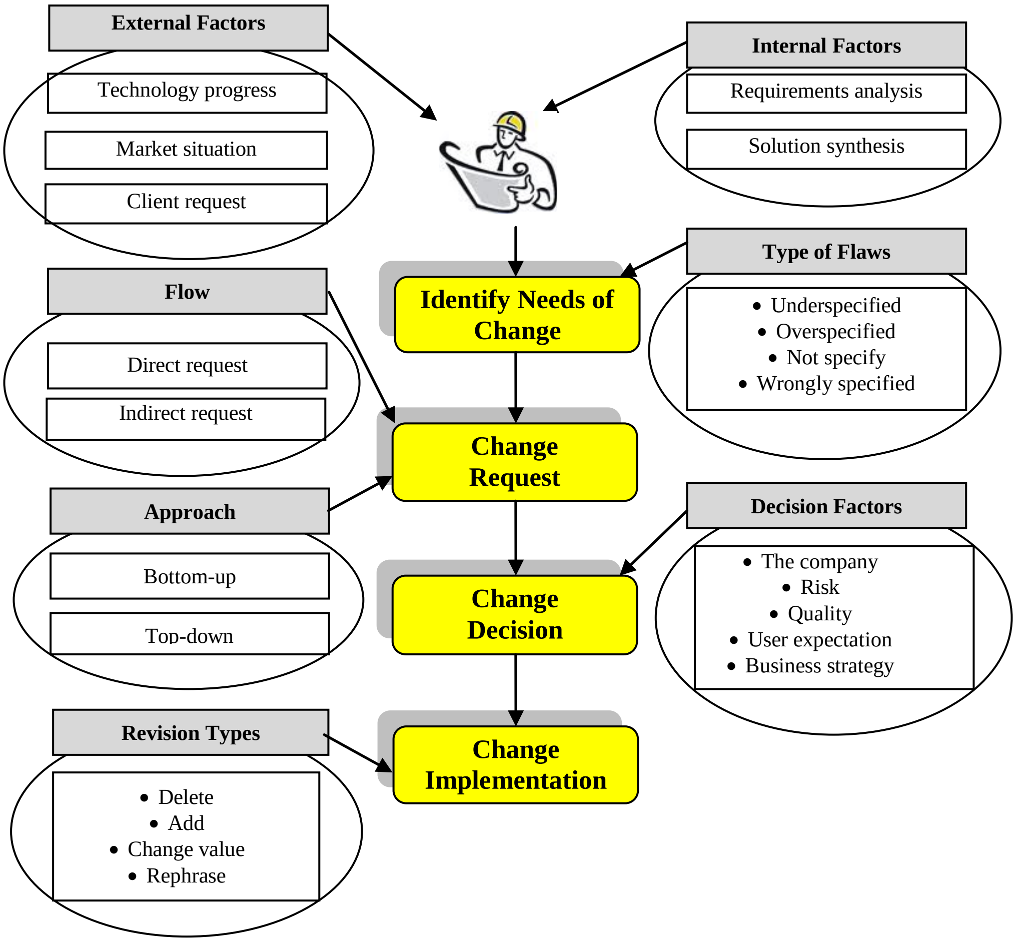


Figure 4.11 Model of information flow for change in requirements

4.2.9 Conclusions

The study was carried out by interviewing six (6) design engineers in a consultancy company. The themes of the interviews were about the creation of specification and changes in requirement during the design process. The study investigated consultants' viewpoints about specification development in the business-to-business context. Since the interviews were open-ended and the participants were allowed to expand the discussion, the study also uncovered a few additional aspects which were helpful to understand the topic of the study.

It was clear that a specification is a central element in the product development process as it provides vital information for design engineers to execute the design tasks i.e. for concept generation and solution evaluation. Considering aspects of product and sources of requirement are essential to formulate requirements in a specification. Thus, in the design process methodology, support such as a method to identify requirements that the design engineers need to execute their design tasks is essential. The support should allow design engineers to develop a specification as simple as possible.

The research also aimed to understand how changes in requirements are carried out during the design process. This understanding includes initiation and management of changes and factors for change occurrence and decision. Changes in requirements are part of the design process as it is impossible to identify a complete requirement during the early phase of the design process.

The mechanism to discover the need to change a requirement emerges as a result of designing activities i.e. *requirement analysis and solution evaluation* or from external factors i.e. *technology changes, market demands, customer requests*. Therefore, a balanced consideration between focusing on fulfilling requirements and being responsive to the external factors are an essential part of the design practice. Requirement development is part of the process of designing so it is a normal activity during the concept design phase. This process is referred to as co-evolution between the problem and the solution domain by several authors [Cross 1997]. The consequences are not severe for designers working alone on a small product but are expected to lead to a more iterative design process, but have greater implication when working as part of design team on a larger, more complex product due to the interfaces with other assemblies.

Changes in requirement during the design process are informal (lack a standard procedure) and frequently changes in requirement are carried out without updating the specification. Design engineers are found to update specifications at the end of the design process. Any modification (change) on an initial specification is always carried out with the clients' approval. Thus, a change in requirement that does not result in modifying an initial specification is considered a normal activity during the design process. In a collaboration project, both internal and external stakeholders are actively involved in initiating changes during the design process.

Understanding all the information content of the upstream process; the change identification and change request process (refer to Figure 4.11), form an essential input to the change decision process. These decision factors are directly fed back to the information content of the upstream process. For instance, in considering a ‘business strategy’, input from external factors may be relevant for consideration as well. In general, changes in requirement during the design process were essential as a way to produce more concrete requirements in a specification. Risks due to changes in requirement are the most important aspect discussed by decision makers when deciding to implement the change or not.

Providing support to facilitate requirement analysis seems a promising direction to pursue in order to mitigate change in requirements i.e. due to the requirement not being defined or wrongly defined, during the task clarification phase. Even though completely defining requirements at the beginning of the design project is impossible to reduce the gap i.e. the number of changes to requirement between the *initial specification* and *full specification*, maybe possible. The process of analysing requirements in a specification should be continual as the design proceeds along the design phase.

4.3 Study 3 - Problem decomposition during the specification development process

The document analysis of three (3) specification documents and supplementary documents e.g. memos and concept sketches (all qualitative data), of three (3) different projects from two (2) different companies were analysed qualitatively based on a pre-defined coding scheme. The coding scheme for the class of issues is related to; functional, lifecycle, interface/environment and product characteristic [Ahmed and Wallace 2003]. The number of pages of specification document in Project A (aero-engine design) is 77 pages, Project B (cooling cassette design) is 7 pages and Project C (wind scanner head) is 3 pages. The complexity (based on the number of components) of projects decreases from Project A, B to C. The study aimed to understand how design engineers consider issues during the requirement formulation process (see detail description in Chapter 3, section 3.9.1). This study has two research questions: 1) what do design engineers do to understand the design problem at the beginning of the product development process? And 2) how do design engineers address and translate the design problem as a list of requirements for a project? The quantification of qualitative data is presented to answer both questions of this study. The results presented in the following section are based upon the projects (Project A, B and C). The themes of the results are:

- Breakdown and distribution of issues considered (refer to sections 4.3.1 for Project A, section 4.3.4 for Project B and section 4.3.7 for Project C)
- Breakdown and distribution of the specific class of issues (refer to section 4.3.2 for Project A, section 4.3.5 for Project B and section 4.3.8 for Project C)
- Breakdown and distribution of requirement statements in the specification document (refer to sections 4.3.3 for Project A, section 4.3.6 for Project B and section 4.3.9 for Project C)
- Patterns of considering issues across the projects (refer section 4.3.10)

4.3.1 Breakdown of issues for Project A

The analysis was carried out to understand the number of levels of issues that have been considered by design engineers before formulating a requirement. The breakdown and the levels of an issue in the specification document are illustrated in Figure 3.3 (see Chapter 3, section 3.9.3). In total, 175 issues were considered in the development of the specification for Project A as shown in Figure 4.12. In general the quantity of issues increased from level 1 to level 2 and decreased from level 2 to 3 and 4. The study found the majority of the issues (at level 1) were decomposed into smaller issues, and some of these issues were decomposed up to 4 levels of detail. There were 27 different issues considered at level 1, these issues then decomposed into 87 more issues at level 2. These quantities decreased to 44 at level 3 and 18 issues at level 4. Issues at level 2, 3 and 4 are not necessarily different issues but some of these issues were reviewed several times within the same levels.

The process of decomposing issues significantly occurs from level 1 to 2, meanwhile from level 2 to 3 and 4, design engineers start to transform some of these issues into requirement statements. Therefore, the quantity of issues slowly decreased from level 2 to 3 and 4. The results show a significant reduction occurs from level 2 to 3 and this is an indication that the majority of requirement statements were formulated at this stage.

This result indicates that in order to produce a good design specification design engineers must have capability to understand and transform the design problem into clear requirement statements. Thus, they must have a capability to decompose issues (*generic issues*) into smaller issues (*focused issue*). This capability would help design engineers to specify a good requirement in a specification. In a separate study [Pimmler and Eppinger 1994] stated “decomposing is a common problem-solving activity whereby a complex problem is solved by first breaking it into a set of smaller problems of lower complexity that can be easily handled”.

It was obvious that the first process in the specification development was problem decomposition and followed by the requirement formulation process. Thus, in the ideal situation an issue should be decomposed into smaller issues up to the level, where further breakdown of the issues are not possible. However, specification developers must keep in mind that the *focused issues* should contribute to achieving the objective of the design.

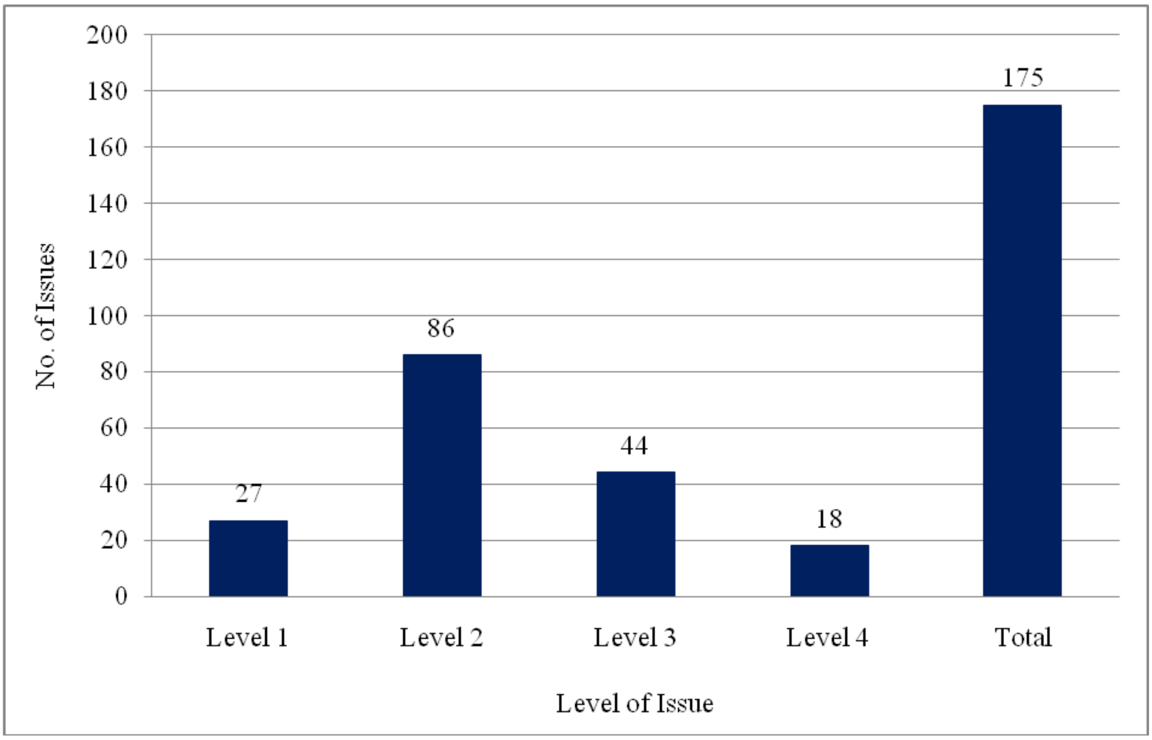


Figure 4.12 Number of issues at different levels of detail for Project A

4.3.2 The distribution of the specific class of issue for Project A

To get more understanding about the issues considered, all these issues were indexed against specific classes of issue that were: functional, lifecycle, interface/environmental and product characteristic related issue [Ahmed and Wallace 2003]. Table 4.13 shows detailed breakdown of these issues in a specific category. The majority of issues considered were related to *interface/environmental* and this represented 38% of the total, *product characteristic* represented 31%, lifecycle related issues represented 23% and issues related to functionality represented 18% of the total issues.

Table 4.9 Number of specific class of issues in Project A

Class of Issues	Functional (FR)	Lifecycle (LCR)	Interface/ Environmental (ER)	Product Characteristics (PC)	Total
No. of Instances	14(8 %)	41(23 %)	66(38 %)	54(31 %)	175(100 %)

4.3.3 Breakdown of requirement statements for Project A

Figure 4.13 shows the breakdown of requirement statements in the specification document for Project A. The total requirements for Project A were 159 and in detail 10 requirements were specified at level 1, 84 requirements at level 2, 45 requirements at level 3 and 20 requirements at level 4. The majority of requirements were specified at level 2, this result indicates the requirements were specified once the design engineers break the issue to two levels of detail. This phenomenon can also be observed as the numbers of issues at level 3 are less than those at level 2. The reduction in the number of issues considered is an indication of the transformation process (from issues into requirement statements).

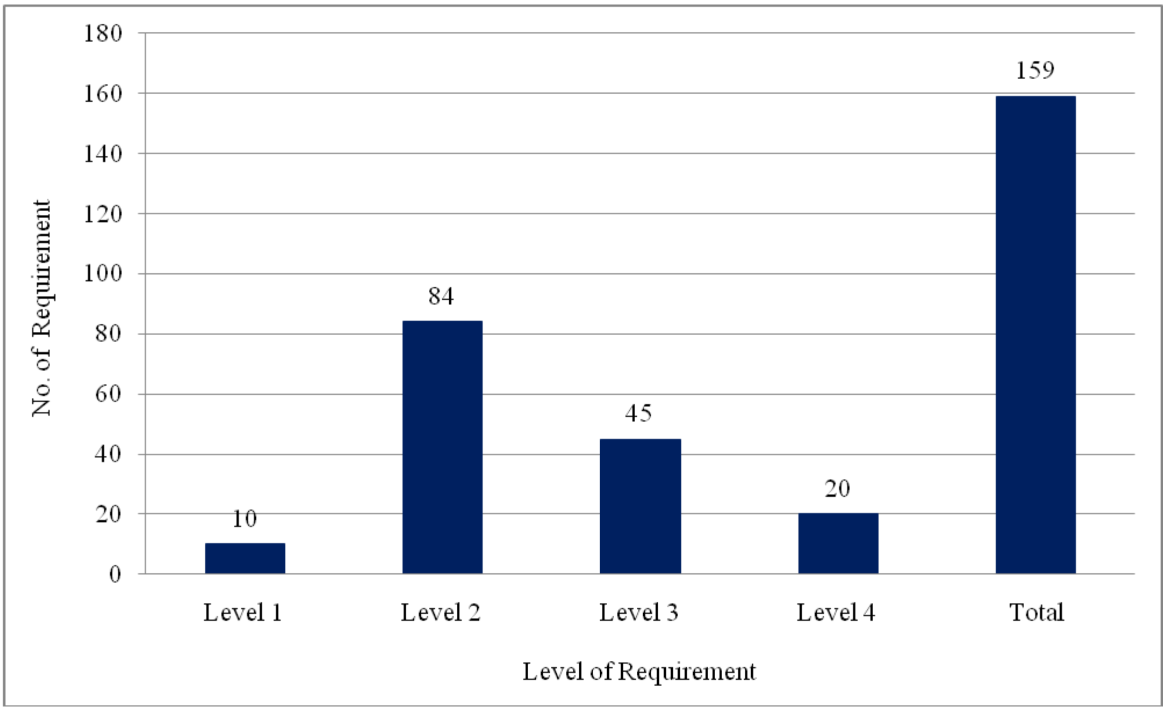


Figure 4.13 Number of requirement statements at different levels of details for Project A

4.3.4 Breakdown of issues for Project B

The objective of this study is to understand how the design problem was decomposed into more detailed problems. In total there were 44 issues considered in the specification document for Project B. The breakdown of each issue in the specification document for Project B is shown in Figure 4.14. The majority of issues at level 1 were decomposed in up to 3 levels of detail. There were 11 issues considered at the beginning (level 1) during the specification development process. These issues then decomposed into more detailed issues that were 22 at level 2 and 11 at level 3.

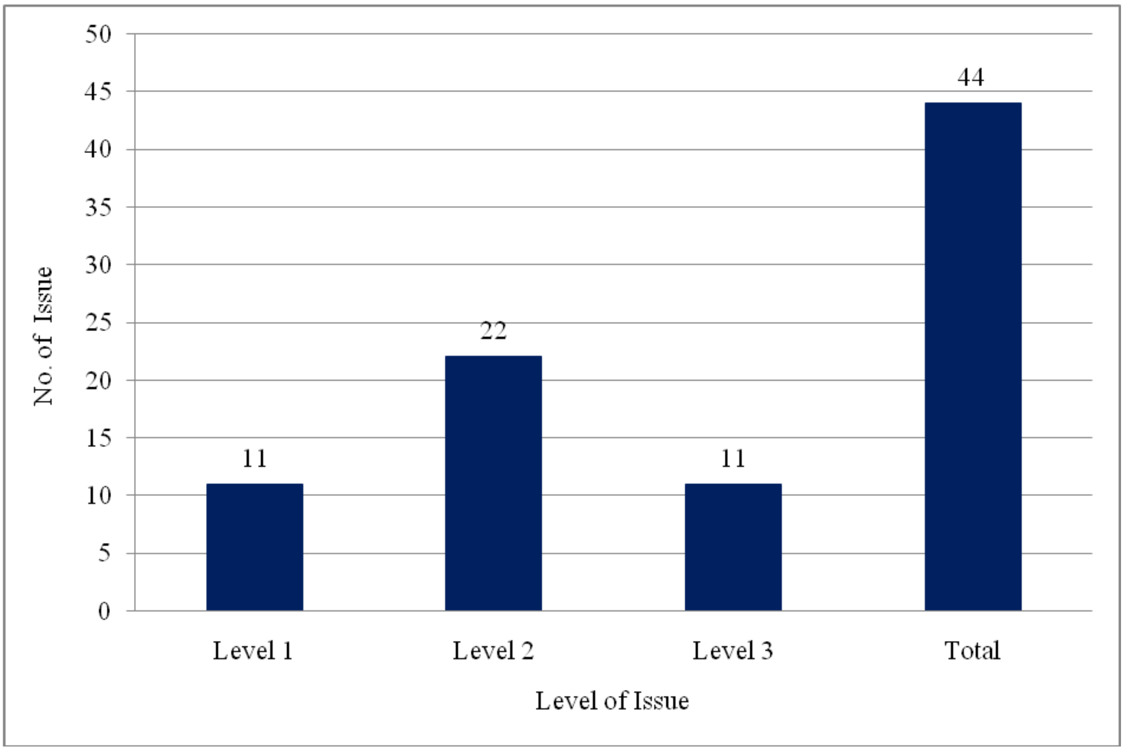


Figure 4.14 Number of issues at different level of details for Project B

4.3.5 The distribution of the specific class of issue for Project B

In general, issues related to *product characteristics* were the major issue considered in developing the specification for Project B, whereas function related issues were considered to a lesser extent. In total, product characteristics represented 39%, interface/environmental represented 32%, lifecycle represented 27%, and functional related issues represented only 7% of the total issues. Detailed distributions of the class of issues at different level of detail are shown in Table 4.15.

Table 4.10 Number of issues for each class of requirement in Project B

Class of Issues	Functional (FR)	Lifecycle (LCR)	Interface/ Environmental (ER)	Product Characteristics (PC)	Total
No. of Instances	3(7 %)	10 (23 %)	14 (32 %)	17 (39 %)	44 (100 %)

4.3.6 Breakdown of requirements for Project B

The distribution of requirements at the different levels of detail is represented in Figure 4.16. In total, there were 56 requirements specified in Project B. The majority of requirements were specified at level 2 are 47 requirements, 18 requirements at level 3 and 9 requirements at level 1. The results indicate that design engineers specified the requirements once they break-up *generic issues* into *solo issues*. The result shows that the majority of requirements were specified after the design engineers considered issues at two levels of details.

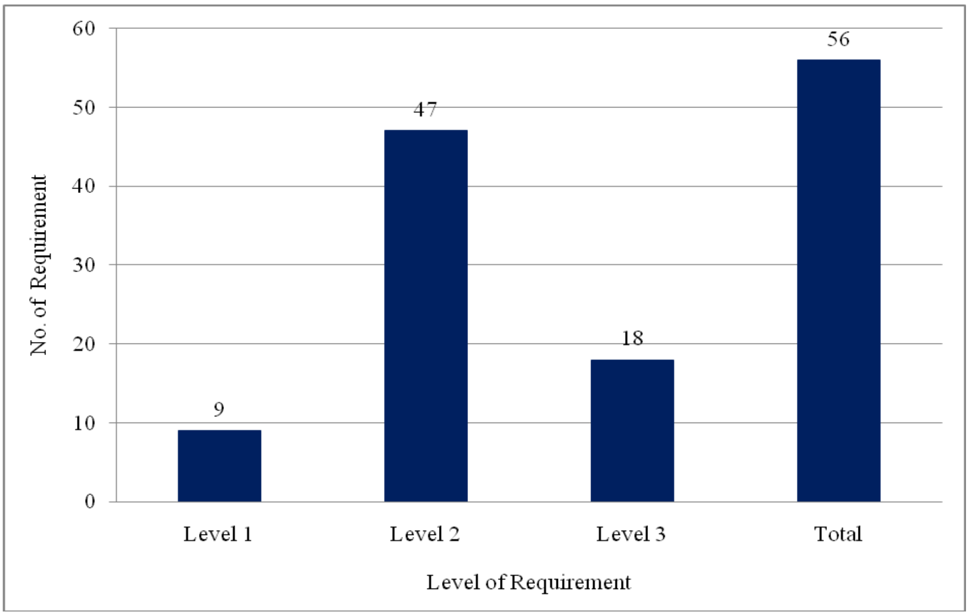


Figure 4.15 Number of requirement statements at different levels for Project B

4.3.7 Breakdown of issues in a specification documents for Project C

The result in Figure 4.17 shows that altogether there were 11 issues considered in Project C. All of the issues considered were at level 1 and none of the issues needed further clarification. All of the issues were classed as 'focused issues'- i.e. at a level for detail design.

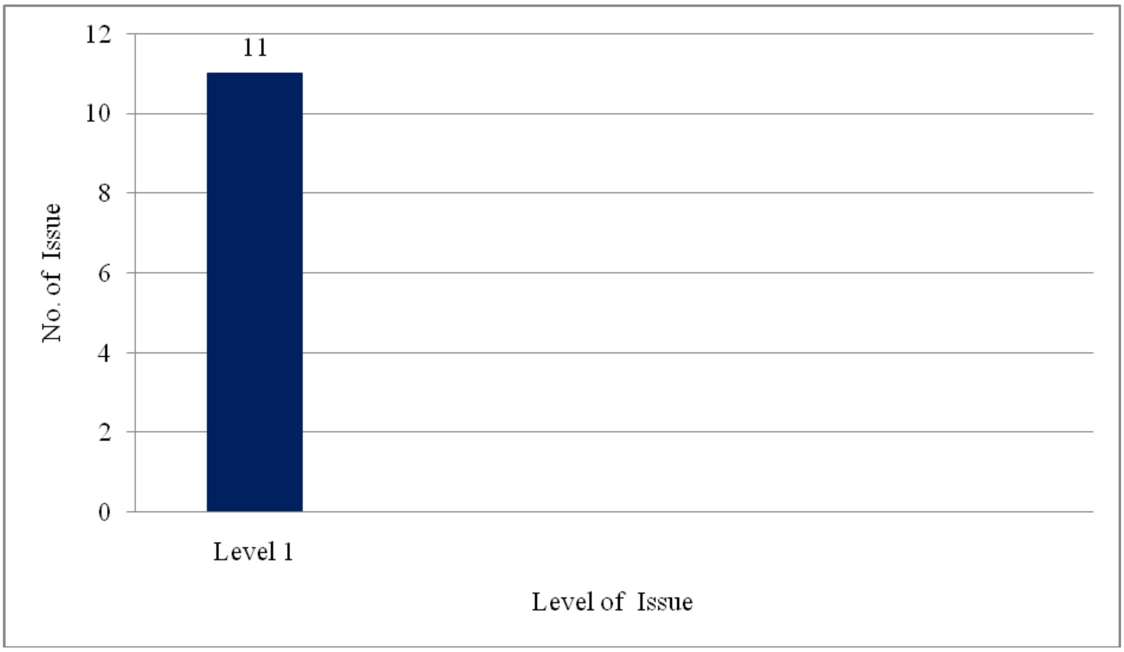


Figure 4.16 Number of issues in the specification document for Project C

4.3.8 The distribution of the specific class of issue for Project C

The results in Table 4.16 show that issues related to *interface/environmental* and *product characteristics* were the main issues considered for Project C and represented 55% and 45% of the total issues. None of *function* and *lifecycle* related issues were considered in this specification.

Table 4.11 Distribution of issues over a specific class of requirement for Project C

Class of Issue	Functional (FR)	Lifecycle System (LCR)	Interface & Environmental (ER)	Product Characteristics (PC)	Total
No. of Instances	0 (0 %)	0 (0 %)	6 (55 %)	5 (45 %)	11 (100 %)

4.3.9 Breakdown of requirements in a specification document for Project C

Figure 4.17 shows the number of requirements in Project C. All the issues at level 1 for Project C were transformed into requirement statements. This result indicates that the *focused issues* would be transformed into requirement statements without need for further clarification.

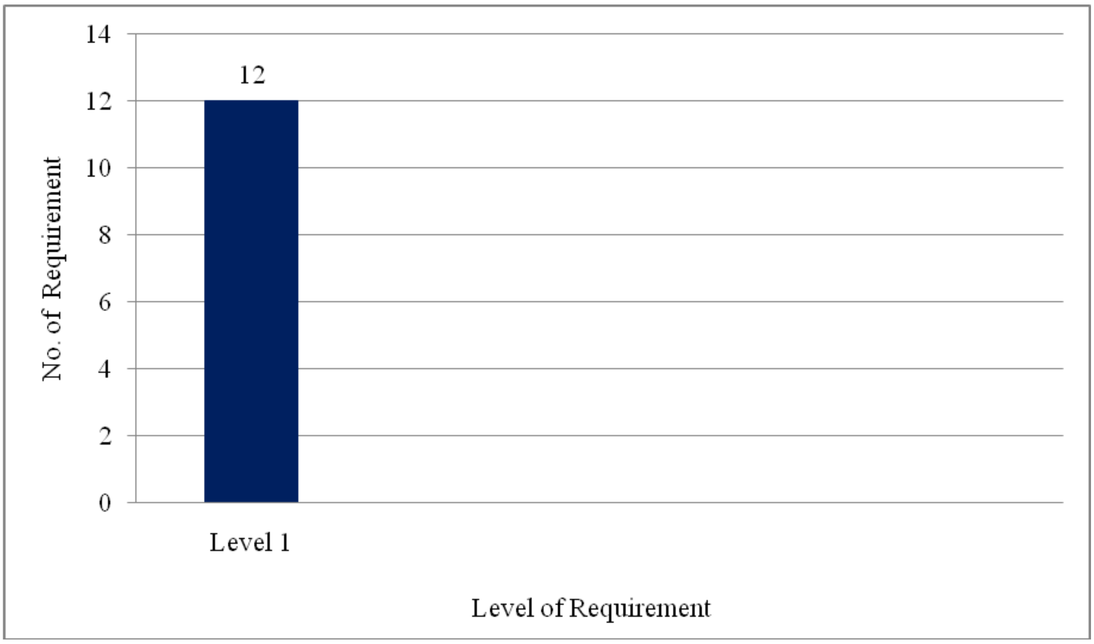


Figure 4.17 Breakdown of requirements in the specification for Project C

4.3.10 Patterns of considering issues across the project

A comparison between the projects with regard to the technique of considering issues leading to requirement formulation was carried out. This analysis was motivated by the finding that while carrying out the problem decomposition process there are several considerations design engineers must make whilst decomposing the design problem, for example, considering the safety or maintenance of the product to be designed. All these considerations are termed as *issues*.

Design engineers always need to consider an issue and its related *issues* in order to formulate a requirement. Design engineers have considered *issues* within the same class (e.g. within *product characteristics* related issues), *e.g. standard----policy, performance---capacity,* as well as considering issues across the classes (*i.e. product characteristics* to *environmental* related issue), *e.g. safety---fire, vibration---stability*.

In Project A, It was found that considerations between the different classes of issues do exist as shown in the following examples:

- Product characteristics and interface/environment
  - *maintainability*
    - *health and human factor*
  - *ergonomic*
    - *handling*
- Product characteristics and lifecycle issue
  - *replace ability*
    - *maintenance*
  - *safety*
    - *protection*
- Product characteristics and functional issue
  - *starting & relight*
    - *performance*
- Lifecycle and interface/environment
  - *installation*
    - *reverse mode*
- Lifecycle and functional issue
  - *starting & relight*

- *monitoring*
- *Interface/environment* and *function*
  - *vibration*
    - *ingestion*

The consideration between *interface/environmental* related to *lifecycle* and *function* does not exist in the specification document of Project B. Meanwhile, none of the considerations about issue and its related issues can be observed in specification of Project C. This result highlighted that it is necessary to consider issue and its related issues in order to specify a requirement. To do this, the design engineer must consider issue within and across the different classes of issue.

4.3.11 Conclusions

This study aimed to understand how design engineers consider issues during the requirement formulation process. In this study, three different projects from twodifferent companies were analysed with regards to the following: 1) the issues considered 2) the breakdown and distribution of issues and 3) the distribution of requirement statements.

The study found, considering issues and its related issues were beneficial in formulating requirements in practice. All issues can be classified into either a *generic issue* or *focused issues.* In all projects, if the issue considered was a *generic issue* then this issue will be decomposed into *focused issues*. Decomposing *general issues* into *focused issues* was the significant activity at the beginning of the specification development. Thus, to produce a good specification document, the capability of design engineers to decompose an issue into detailed issues is essential. In principle, issues related to lifecycle, interface/environment and product characteristics are always considered during requirement formulation. Meanwhile, *function* related issues were rarely considered in the specification document, it may be due to the *function* related issues were specified in another document such as in *functional specification*. Another possibility maybe as the functionality of the design has been understood by design engineers it therefore may not be necessary to be specified in the specification document e.g. in Project C.

Differences between projects were observed from the number of *focused issues* considered in every project. Since each project is designed for a different purpose the *functional* issues between them are different too. The results show that understanding what issue to consider is important knowledge in developing a specification. However, understanding a good technique to consider issues was an extra advantage to the design engineers when developing requirements.

It was observed that design engineers employed several techniques while considering issues. They have considered issues in three patterns: 1) consider several related issues within the same class 2) consider several related issues between the different classes and 3) a combination of both. Therefore, a thorough understanding about the relationship between issues (within their class and between the classes) and relationship between an issue and requirement statements would help designers to transform issues into clear requirement statements.

With regard to the requirement statements in a specification document, the study found that the lowest level issues were addressed as a requirement statement. Sometimes the specified requirements were not relevant to the issue at level 1. Therefore, tracing the related issues assists in understanding the reason behind the requirement statements. This study has provided some ideas for the techniques to consider issues in the context of developing a good specification.

CHAPTER 5: SUPPORT METHOD

This chapter describes both the Prescriptive Stage (PS), which is devising the design method, and the Descriptive Stage II (DS II), which is the preliminary evaluation of the devised method that supports the overall research methodology. Several criteria that were considered in developing a practical support are also outlined. Additionally, this chapter describes a preliminary evaluation methodology of the method of support.

5.1 Statements and criteria to support the development of a practical support

The following results of the three studies are the inputs to the development of the design support:

- Change in specification is one of the major causes of EC's during the three different phases and all phases of the product's lifecycle (Chapter 4, section 4.1.1).
- Knowledge and experience of internal customers is an important asset to identify the need for a change. Thus this asset needs to be captured as feedback in order to develop good requirements in a specification (Chapter 4, section 4.1.3).
- Change initiators are not always aware of the risks of a change that they have proposed. A change can be very risky, and thus it is essential to mitigate EC's (Chapter 4, section 4.1.6).
- Internal customers i.e. design engineers, assemblers and production engineers, are the major contributors to the EC's initiation (Chapter 4, section 4.1.5).
- Design engineers mainly rely on their own experience and knowledge in developing a specification for a project (Chapter 4, section 4.2.2).
- It was found that design engineers had considered the aspects (issues) and the source of requirements repetitively during the course of the specification development process (Chapter 4, section 4.2.3).
- Analysing the existing requirements and evaluating the on-going solution assist design engineers to identify the need for changes of requirements (Chapter 4, section 4.2.7).

- It was found that design engineers had considered the issues and decomposed the issues into several issues (sub-issues) in order to facilitate the requirement formulation process (Chapter 4, section 4.3.2 and 4.3.5).

5.2 The development of the design support

The motivation to develop the design support process that is aimed at facilitating the task clarification process is derived from Study 1: document analysis of EC's request reports, whereas the important criteria for devised support were derived from:

- Study 2: interviews with product development consultants who have had experience in developing a specification for design projects; and
- Study 3: document analysis of the three specification documents of the three different products from the two different companies.

The devised support is aimed at improving the design process by focusing on the task clarification process. When developing a support to help design engineers to translate the design problem into a set of requirements, the following issues were considered important:

- Identification of the *design process* that the method intends to support
- Identification of the *user* of the support
- Identification of the *elements* that the design engineers considered as leading to the identification of requirements

The findings from Studies 2 and 3 have shown that design engineers were found to have considered *issues* and *requirement sources* in order to formulate the requirements for a product. Additionally, design engineers always try to clarify the design problem by considering several issues and translating these issues into requirement statements in a specification. The issues that design engineers considered were related to the particular product, e.g. s*afety issues*, *manufacturing issues* etc. and they had decomposed a single issue into several relevant issues (see some examples in Chapter 4, section 4.3.7).

This method is also designed to increase the awareness of the design engineers about the issues that they need to consider for formulating the requirements in a specification. Therefore the devised support tends to encourage the design engineers to carry out two main activities; *considering issues* and *decomposing issues*. Considering and decomposing issues help the design engineers to clarify the design problem and subsequently to assist the design engineers in formulating requirements for a specification. The support has been developed by considering all of the relevant results from the three studies that have been outlined in section 5.1. Thus, the devised support focuses on the following:

- The *checklist* of the issues that need to be considered (refer to section 5.2.1). The checklist aims to ensure that the design engineers consider all the necessary issues.
- The *stakeholder* in the list of issues (refer to section 5.2.1). All the stakeholders are considered as the origin of the requirements. Thus considering stakeholder requirements help in producing a comprehensive list of issues.
- The *questions* to be asked for considering issues (refer to Figure 5.1). The questions help design engineers to determine the steps to consider an issue.
- The *strategy* to decompose an issue and successively to formulate the requirement (refer to section 5.2.2). This strategy is aimed at guiding design engineers in formulating requirements based on the issues considered.

The devised support also emphasises the strategy adopted by design engineers to decompose a single issue into smaller issues and finally to translate the combination of these issues (issue and sub-issue) into a set of requirements. The devised support does not support the design engineers in identifying the relationship between the issues as these relationships are complex and require further investigation.

5.2.1 List of the issues

A checklist of the issues is required to ensure that the design engineers are aware of the issues that they need to consider while formulating requirements for a specification. This also ensures that all the important issues are considered without missing any. The list of issues was derived by considering the stakeholders of a design project, including the end customer, the manufacturer, the design engineers, the test engineers, the system integrator, the distributor, maintenance personnel, society and legislators. Figure 5.1 shows the issues and questions to be asked by the design engineers when considering an issue. Not all issues are relevant for a specific project. For instance, the *aesthetic* issue may not be relevant for a product that is not exposed to human viewing. The generic questions that are located at the centre of the issues (refer to Figure 5.1) create awareness amongst the design engineers about the importance of translating an *issue* into *a requirement* statement. It also requires identifying the relationship between *issue* and *requirement*.

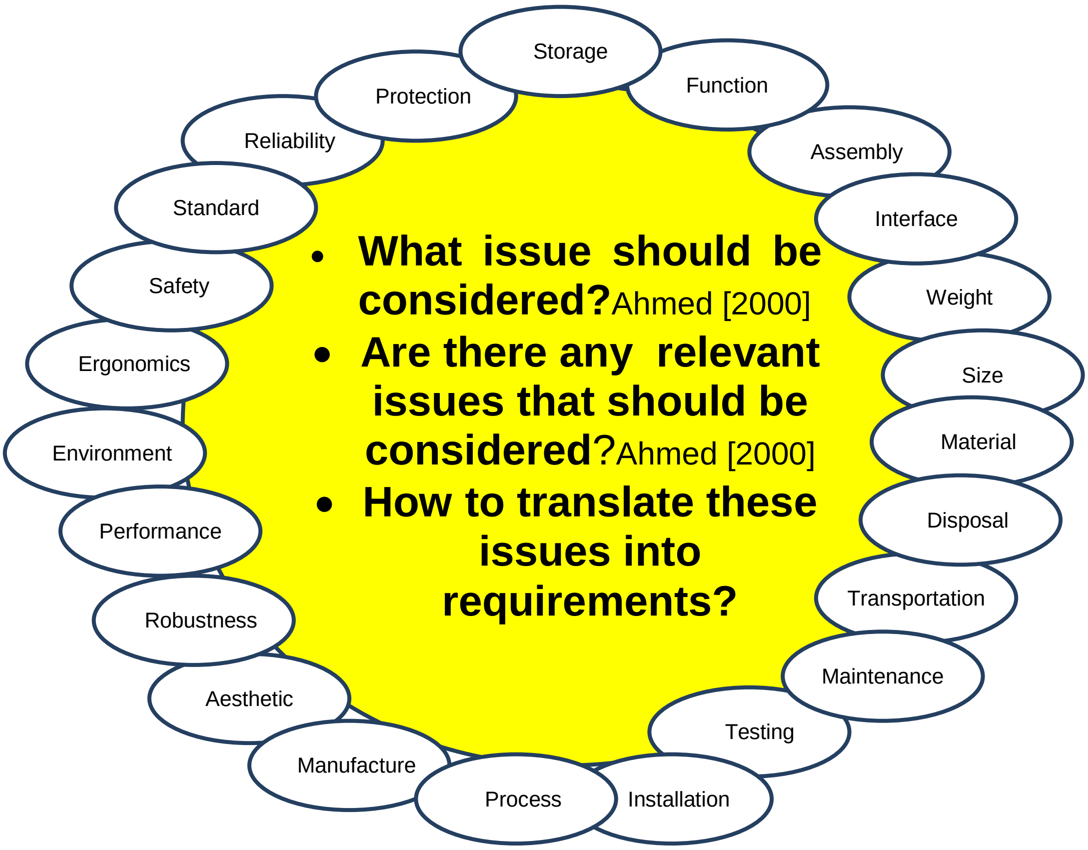


Figure 5.1 List of issues

5.2.2 Techniques to decompose issues and formulate a requirement

The support also aims to assist design engineers in translating an issue as a requirement in a specification. In the devised support, the technique of decomposing an issue into several issues is proposed. The technique to translate an issue into a requirement is derived from the findings of Study 3. The results of Study 3 (refer to Chapter 4, section 4.3.2, 4.3.5 and 4.3.8) show that in order to ensure that each single issue is fully addressed, each issue needs to be decomposed into several issues and each of these combinations (issue and sub-issue) need to be addressed as requirements. Each issue is addressed by a single requirement. The outline of the technique for considering an issue and addressing this issue as a requirement is as follows:

(1) Choose ONE ISSUE from the list (refer to Figure 5.1) that is important for developing the product.
(2) Identify ITS RELATED ISSUE from the list (refer to Figure 5.1).
(3) CONSIDER BOTH ISSUES and define the relationship between them.
(4) Translate them into a requirement statement (refer to Figure 5.1).
(5) Go to step 2 (identify other related issues, IF ANY)-refer to Figure 5.1.
(6) Proceed to steps 3 and 4.
(7) Choose ANOTHER ISSUE from the list and repeat this process (steps 2 to 5).

The outline of the technique is aimed at facilitating design engineers in addressing each issue with appropriate requirements.

5.3 Evaluation of the support

The devised design support, in principle, is aimed at assisting design engineers to decompose an issue into smaller issues and eventually to address the combination of these issues (issue and sub-issue) into a requirement. To verify that this aim is achieved, two evaluations methods were carried out on the devised support; namely controlled experiment and interviews survey. This section describes the evaluation methods (refer to section 5.3.1) and the findings of the evaluations (refer to section 5.3.3). The evaluation consisted of three parts: 1) a fifteen minute introduction of the devised support process to the *test group*; 2) a ninety minute assignment for both groups (*control and test group*) to produce a requirements list for a product, and; 3) post evaluation interviews with the participants in the *test group*. The results of the evaluations are analysed based on the Kirkpatrick model of evaluation (refer to section 5.3.2).

5.3.1 Introduction to the design support process

The first fifteen minutes of the evaluation was an introduction to the design support and evaluation procedure. The purpose of the support and the reason for developing the support were explained to the participants. Each of the sections in the design support booklet was verbally explained to the participants in the *test group*, together with the given example in the support. The role and expected output from the assignment was explained to the participants. The participants were also informed that the purpose of the experiment was not to evaluate them but to evaluate the devised support. As a motivation to the participants to take this assignment seriously, they were informed that a small reward would be given to them as a token of appreciation.

The participants were divided into two groups (*test* and *control* group), before the introduction to the design support. The reason and differences between these groups were explained to the participants. At first, six volunteers were requested to be the participants in the *test group*. Fifteen minutes were spent for the introduction to the support. They were allowed to ask any questions with regard to the devised support before the experiment started. The participants in the *test group* were reminded many times to ensure that they used the devised support for the assignment. The introduction to the support was carried out without the presence of the participants in the *control group*. All the participants were asked to give their full commitment for the assignment and they were encouraged to act as design engineers in the company. They were also reminded that any discussion was not allowed during the experiment but at the same time they were allowed to ask any questions if they needed further clarification about the assignment.

5.3.2 Participants and evaluation procedure

The evaluation of the design support was carried out within a *controlled experiment*. In total, twelve design students participated in the evaluation of the devised support. All students were in the final year (year 4) of their study in the Department of Design and Innovation, Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka (UTeM). They had almost the same level of knowledge and experience of developing a basic specification. The commonly known approaches, i.e. using a checklist to develop a basic specification, were taught to them during the second year of their studies. They were randomly selected from the sixty design students available at the time that the experiment was carried out. They were divided into two groups: 1) Group 1 (*test group*), carried out the task with the devised support; and 2) Group 2 (*control group*) carried out the task without the devised support process. Both groups had to carry out the task clarification process, and were asked to produce a list of requirements for the same product, a fastening device, at the end of the controlled experiment (refer to Appendix D for details). Students in Group 1 had to use the devised support for the assignment, whereas students in Group 2 were free to use any method they knew for the assignment. The controlled experiment lasted 90 minutes. In the experiment, *time, knowledge, gender and assignment* were set as the controlled variables. Upon completing the given assignment, students in Group 1 were asked to give their written feedback about the devised support. (See details about the post evaluation questions in section 5.3.2).

The aim of the controlled experiment was:

- To measure the effectiveness of the devised support (independent variable) in facilitating design engineers in formulating the requirements for a specification. The requirement list produced by the two groups was analysed and compared. The assessment of these requirements are based on the following outputs (dependent variables):
  - the number of issues and sub-issues considered
  - the number of issues translated into requirements

The evaluation also aimed to collect comments from the participants in the evaluation. The effectiveness of the devised suppor*t* was measured through the following hypotheses:

- *Hypothesis 1*: the use of the devised support will result in the number of sub-issues being more than the number of issues.
- *Hypothesis 2*: the use of the devised support will increase the number of issues translated into requirements.

5.3.3 Kirkpatrick model of evaluation

The Kirkpatrick model of evaluation is one of the models primarily used to evaluate new methods, tools and training programs in academia and industry [Ahmed 2000]. The requirement list that was produced by the participants at the end of the controlled experiment and the written answers of the participants from the interview survey was analysed based upon Kirkpatrick's model of evaluation. The model consists of four levels of evaluation as follows:

- *Reaction*: the response of participants to the devised *support.*
- *Learning*: what the participants learned from the devised *support* and how easy the devised *support was* to learn.
- *Behaviour*: the change in the participants' behaviour based on what was learned from the devised *support* and the number of issues and sub-issues that they considered in developing the requirements list.
- *Result*: the impact of the devised *support* upon the organisation

The interview survey was carried out on the completion of the controlled experiment. For all the participants that were in Group 1 (*test group*), the questions were related to four levels of the Kirkpatrick model namely; *reaction, learning, behaviour and result*. The questions for the interview survey are shown in the Table 5.1. In case the written answer from the participants was not clearly understood, a personal interview with individual participants was used to clarify their answers. During the interview the researcher together with the individual participant tried to rephrase the sentences of the given answers without changing its original meaning.

Table 5.1 Evaluation questions of interview

No.	**Question**	**Component**
Q1	What did you think (learn) about this support process?	*Learning*
Q2	How easy is the support process to use?	*Reaction*
Q3	Is there any change in your behaviour when using this support process?	*Behaviour*
Q4	What did you like about this support process?	*Reaction*
Q5	Did you consider issues and its related issues to carry out the task clarification process previously?	*Behaviour*

5.3.4 Results of the preliminary evaluation

The controlled experiment and post evaluation interviews have been analysed based upon the four levels of the Kirkpatrick model. The results from both the evaluations (controlled experiment and post evaluation interview survey) are presented based upon the *reaction, learning, behaviour and result*. The *reaction* and *leaning* are assessed based upon the interview survey, the *behaviou*r is assessed based on the interview survey and analysis of the requirements list and the *results* are purely from the analysis of the requirements list.

Reaction

The participants from the *test group* (group 2) were asked to give their reaction to the devised support (refer to questions 2 and 4 in Table 5.2). The participants were asked to give their reflection about the simplicity and something that they liked about the devised support. In general all of the comments were positive and several good attributes of the devised support were mentioned. The comments can be divided into two categories: 1) the structure; and 2) the content. The participants found the method easy to use and they liked the step by step process of formulating the requirements from the issue. The following comments are quoted from the participants.

EG1-1

"The support is easy to use due to the step by step process. From the given information, the process will guide engineers to focus on the issue. Each issue is related to other issues and makes it closer to the requirement".

EG2-S

"The support is very easy to use because the organisation is very clear. It is easy because the step by step process is shown by a flow chart. ………the issue is represented in the small circle, making it very interesting. …..the explanation and the examples make the support very clear and helped me to complete the task".

EG3-S

"The support is very easy to use as the steps to formulate a requirement from the issue are given. The glossaries of each issue helped me to understand the issue".

Learning

The participants were asked what they learned from the support (refer to question 1 in Table 5.1). Four of the participants mentioned that the devised support helped them to consider an issue. Using the support they learned how to relate one issue to another issue and this subsequently helped them to translate these issues into requirement statements. The following statements were quoted from the participants. One of the participants mentioned that the support made him aware of the issues that needed to be considered in order to formulate the requirements for a product. One of the participants mentioned that the support makes the natural flow of the requirement formulation process explicit i.e. consider an issue and relate this issue to another issue. The participant learned how to consider issues and to decompose an issue into sub-issues.

EG2-S

"This support is a very good method to use for formulating product requirements in a specification. All issues need to be related to another issue to ensure that a better requirement can be formulated".

EG4-S

"The provided support is very useful as it provides a clear method on how to translate an issue into a requirement statement. Without the support, the process of translating the issue into a requirement will definitely be more difficult. Overall, the support really helped and guided me to accomplish the task".

EG5-S

"I think this support is quite useful in determining the specification requirements. The given method really illustrated an easier way to identify and formulate the requirements. I also learned that it is much easier if we list down all the possible issues and find another issue that is related to this issue. Subsequently, we can try to establish the relationship between these issues. I can say this support is a manual for design engineers".

Behaviour

The *behaviour* of the participants while considering an issue during the task was observed based on the requirements list that they had produced at the end of the experiment. In addition, the participants were asked whether the support had changed their behaviour during the requirement formulation process (refer to question 3 and 5 in Table 5.2). The number of issues and sub-issues considered by the participants during the process was counted as it indicated the behaviour of the participants.

Thus the behaviour of participants was evaluated through the number of issues and sub-issues considered by participants in both groups (*control* and *test groups).* In total, the result of the experiment, as depicted in Table 5.2, shows that the number of issues considered by the *control group* is higher than the number of issues considered by the *test group. The control group* considered 67 issues whilst the *test group* considered 37 issues. However the number of sub-issues considered by the *control group* was 40 and 98 by the *test group*. Generally, all participants in the *control group* (except EG2 and

EG3) had considered more issues than sub-issues. In contrast the participants in the *test group* had considered fewer issues than sub-issues. The results show that the participants in the *control group* tended to consider an issue and translated them into the requirement statement without considering any sub-issues whereas the participants in the *test group* tended to decompose an issue into smaller issues (sub-issues) during the task clarification process. The comparison between both groups shows that the devised support was able to help participants to decompose an issue into sub-issues, successfully confirming *hypothesis 1*. In addition the support had changed the behaviour of participants while considering issues during the requirement formulation process. However this behaviour is the natural behaviour of the participants as the participants in the *control group* also considered sub-issues instead of considering the main issues. It was found that, considering sub-issues before formulating a requirement was less emphasised by the participants in the *control group* (except EG2 and EG10, see Table 5.3).

In addition the participants were asked about how the support had changed their behaviour while formulating the requirements. This demonstrates that the change in behaviour as a result of the support led to more issues being considered. The following are a few quotations from the participants.

EG2-S

"I would not have considered issue and related issues. If I didn't have the support, I would use the standard step to produce the requirements".

EG4-S

"Previously, the issue and related issues are also considered but not very detailed as I was not given the support. With the support, the issue and related issues are explained in more detail".

EG5-S

"Before this, I had not considered this (issue and its related issues). What I did, was to find out an issue and directly translate it into the requirement and I think it was much harder than this time".

Table 5.2 Number of issues and sub-issues considered

	Participants Identification	No of Issues	No of Sub Issues
Control Group	EG1	11	6
	EG2	8	11
	EG3	10	12
	EG4	11	3
	EG5	13	4
	EG6	14	4
	Total	**67**	**40**
Test Group	EG1-S	6	14
	EG2-S	6	14
	EG3-S	7	15
	EG4-S	8	20
	EG5-S	5	15
	EG6-S	5	20
	Total	**37**	**98**

Results

The requirements list produced by the participants in both groups *(test and control groups)* were analysed to investigate the number of issues translated to requirements. In general, the number of requirements produced by the participants in the *control group* was 60, and 62 by the *test group* as shown in Table 5.3. The results have shown that there is almost no difference in terms of the number of requirements produced between the two groups. This result indicates that the devised design support process did not really help participants in formulating more requirement statements for a product. However, since both groups were assigned to produce the requirements for a simple product, it may be difficult to observe the differences between the numbers of requirements produced by each group. The impact of the support to the result (number of requirements produced) is not obvious as the participants in the *control group* were also able to produce the requirements for a simple product without any support. In addition, the knowledge and intelligence of the participants may help them to address this particular issue in more detail.

Table 5.3 Number of issues translated into the requirements statement

	Participants Identification	No of Issues	No of Sub Issues	No of Requirements
Control Group	EG1	11	6	14
	EG2	8	11	5
	EG3	10	12	10
	EG4	11	3	8
	EG5	13	4	8
	EG6	14	4	15
	Total	**67**	**40**	**60**
Test Group	EG1-S	6	14	12
	EG2-S	6	14	8
	EG3-S	7	15	8
	EG4-S	8	20	11
	EG5-S	5	15	9
	EG6-S	5	20	14
	Total	**37**	**98**	**62**

The number of issues addressed in the requirements informs us of the relationship between the issues, i.e. how the issue of *weight* influences the issue of *performance* of a product, or how the issue of *weight* influences the *material* of the product. The relationship between the issues will inform the design engineers of the objective of the requirements. In general, the number of issues in the requirements between both groups was calculated and presented in Table 5.4. It was found that 82% of the requirements formulated by the participants in the control group have one issue and the remaining 12% have two issues. In the test group, 42% of the requirements have one issue and 58% of these requirements have two issues. However, how effective the requirements with the two issues are over the requirements with the one issue cannot be proven as this point requires further study.

Table 5.4 Number of issues stated in the requirements

	Participants Identification	No of Requirements	No of issue in the requirement	
			One Issue	Two Issues
Control Group	EG1	14	12	2
	EG2	5	5	0
	EG3	10	8	2
	EG4	8	7	1
	EG5	8	5	3
	EG6	15	13	2
	Total	**60**	**49 (82%)**	**10 (12%)**
Test Group	EG1-S	12	7	5
	EG2-S	8	4	5
	EG3-S	8	2	6
	EG4-S	11	2	9
	EG5-S	9	6	3
	EG6-S	14	8	6
	Total	**62**	**26 (42 %)**	**34 (58%)**

5.4 Conclusions

The devised design support had been developed based upon the findings of the Descriptive Study I (DS I) in Chapter 4. The support assisted the design engineers by informing them how to consider issues and translate these issues into requirements. The method consists of a list of issues which is represented in a small bubble arranged as a ring. In the centre of the ring, three generic questions are stated to inform the design engineers the way to consider issues. The outline of the steps to consider issues and the example provide an effective technique to formulate a requirement from an issue. The glossaries of the issues help designers to understand the meanings of the specific issues.

The method has been evaluated by asking design students to formulate a list of requirements for a particular product. The list of requirements produced by the design students is used to evaluate the effectiveness of the design support to carry out the task clarification process. The evaluation of the requirements is based on the four levels of the Kirkpatrick model (refer to section 5.3.2).

The initial reaction of the participants (design students) based upon their comments was very positive. The design students were pleased with the support as the process shows them a step by step method of formulating a requirement from an issue. They were also happy with the structure and content of the devised support. The participants also learned how to consider issues and the relationships between the issues.

A change in the behaviour of the design students while considering issues in order to formulate a requirement was observed. The design students in the test group tended to decompose an issue to smaller issues (sub-issue) before they formulated the requirements. This result has shown that the devised support was able to assist design students to decompose an issue into sub-issues. As more issues decomposed, one would expect that the support would have increased the quality of the requirements. However the impact of the design support to the number of the requirements produced by both groups was not determined. The reason could be due to the fact that the complexity of the product is low. Thus, the design students without the support were also able to produce the requirements for the product very easily. In addition, the effectiveness of the requirements with the two issues to assist design students for the design synthesis could not be proven during this experiment and therefore requires further investigation. In conclusion, the support has been able to assist the design students only to a certain extent and thus needs improvement (refer to Chapter 6 in Section 6.3).

CHAPTER 6: CONCLUSIONS AND FUTURE WORK

This chapter summaries the overall conclusions drawn from this research, including: 1) the literature review; 2) the research approach; 3) the findings, and; 4) the proposed method of support and suggestion for future works to be carried out (see section 6.5).

6.1 Main conclusions from literature review

The literatures of the three relevant areas are reviewed to obtain a basic understanding of the gap in the current research with regards to the specification. The three areas are: the Design Methodology; the Specification and; the Engineering Changes (ECs).

The review on the design methodology has shown that, there are some differences between a descriptive and prescriptive design model with regards to requirements in a specification. In the prescriptive model, a complete requirement should be identified, formulated and written in a specification document at the start of the design process. In this situation, the requirements provide a basis for the design synthesis and criteria to evaluate of the on-going solution. Thus, design is treated as a rational *problem- solving process*. On the other hand, in the descriptive model the requirements in a specification co-evolve during the design process between the problem and solution space. Requirements in a specification will set the frame for the design engineers to take action to improve the current situation. Thus, the descriptive design model defined design as a *reflection-in-action process.*

Prescriptive models of the design process have reached the consensus that there are four common stages in the design process, namely: 1) task classification, 2) conceptual design, 3) embodiment design and; 4) detail design stage. The prescriptive model e.g. Pahl and Beitz' model (refer to Chapter 2, Figure 2.2) focuses on the role and position of a specification in the context of the entire design stage, whereas the descriptive models of the design process generally focus on the conceptual design stage and are developed based upon the cognitive psychology of the design engineers as they carry out particular design tasks e.g. decision making process. The descriptive models are appropriate for understanding the cognitive and creativity of individual, however they are not sufficient to understand the design process in the organisation setting. In addition, there is no clear relationship between the evolution of requirements and the management a specification e.g. how is co-evolution of requirements during the design process influencing the initial specification?

The research has reviewed relevant literature in the field of specification and requirements. The review found that the terms ‘specification’ and ‘requirement’ are used interchangeably by different authors in their literature. Thus, understanding the context in which the term is used is essential to understand whether the term used by the author is for ‘an artefact’ or ‘a statement’. Regardless of the term used by the authors in literature, the significance of ‘specifications’ or ‘requirements’ as an important entity in the design process is agreed on by all authors as it carries the stakeholders’ need for the product to be designed. Acknowledging the role of specification in the design process, several general guidelines and methods have been proposed to develop a good specification. Unfortunately, these methods often lack of empirical evidence therefore need for further investigation.

The review on ECs shows the impact of ECs to the product development process are paramount, and can be treated positively e.g. increasing product variants, or negatively e.g. increasing lead time. It can be concluded that, proper management of the ECs process is essential for the companies to take advantage as ECs occur. However, methods to reduce ECs during the development of a product, such as ECs carried out in the same version/variant of product during its development, need to be addressed as well, e.g. for the product with long lead-times. Since ECs result of changes in specification, an understanding of the relationship between specifications and ECs is necessary for feedback to develop a better specification at the start of the design process.

6.2 Main conclusions from Descriptive Study 1 (DS 1)

Three studies were carried out during the DS I stage. Study 1 (refer to Chapter 3, section 3.1) was carried out to understand changes in specification and the signification of these changes to ECs during the product’s lifecycle. Study 2 and 3 (refer to Chapter

3, section 3.2 and 3.3 respectively) is to understand the evolvement of a specification during the product development. Study 2 focuses on the specification development process and changes in requirements during the design phase. Study 3 focuses on understanding the action of design engineers in order to clarify the design problem during the task clarification phase.

It was found that, the development of a good specification in the early phase of the product development process is important as changes in specification is one of the main reasons for ECs during the product's lifecycle contributing to 13%-40% to the total ECs during the three different phases (development, manufacture/built & testing and service phase) and around 18% to all phase of the product's lifecycle.

Knowledge and experience of an internal customer to discover the need for changes are valuable to learn from, to ensure the need for changes can be discovered as early as possible during the product development process. These experiences are necessary to identify the need for a change as the *formal methods* are less effective to discover all changes and therefore need improvement.

Several issues have to be considered when designing a specification i.e. the technical content, the roles of the specification during the design process. This is to ensure ECs due to specification deficiencies are unlikely to occur, particularly in the later phase of the product's lifecycle. Since change in specifications are concentrated during the manufacture/build & testing phase, the underlying reasons for these changes are related to the issues at the corresponding phase. Thus, defining all specifications that are related to manufacture, build and testing are the most important issues to be addressed as to reduce ECs due to change in specifications.

A simple method to facilitate design engineers to carry out task clarification process (to develop a specification) is essential. Considering aspects (issues) and requirements sources continually along the design process helps design engineers to identify requirements for a product. It was found that, an ability to decompose an issue is essential criteria for the design engineer to formulate a requirement. An ability to consider an issue together with its related issues is an advantage to design engineers during requirement formulation process.

6.3 Main conclusions from the Prescriptive Study (PS) and evaluation

Based upon the results of the three studies carried out during DS I, a design method was developed to facilitate design engineers to become aware of the issues that they have to consider while formulating requirements in a specification and to carry out the problem decomposition process. The support is developed to ensure the design problem can be appropriately addressed by a set of requirements in a specification.

A preliminary evaluation of the devised method has been carried out within a controlled experiment with the design students. This experiment is used to compare the results of two groups of students; with support (test group) and without support (control group) with regard to the three criteria's: 1) number of issues considered; 2) number of issues decomposed and; 3) number of issues addressed. In addition, an interview survey was carried out to the participants that had been supplemented with the support as to collect their comments about the support. The results of these two evaluations were analysed based on the Kirkpatrick's model of evaluation.

On average, the results of evaluation show that the design students in the *test group* are always better in considering issue as they produced more sub-issues than those in the *control group*. However the number of requirements produced by both group was almost the same. This result may due to the complexity of the product being too low. Additionally, the participants in the *test group* were considering the combinations of issues (issue and sub-issue) more frequently before they formulate a requirement. However, the effectiveness of a requirement containing the combined issues over a requirement with a single issue is not proved yet. In general, the support met the objectives as it is created for the research study but needs further improvement, evaluation and validation.

6.4 Reflection on the research methods

Three studies were carried out to understand the significance of changes in requirement to ECs and the evolvement of a specification during the product development process. The three studies were carried out though two different approaches: 1) document analysis and; 2) interviews. Each research approach had its own advantages and disadvantages.

The *document analysis* (ECs request reports) of Study 1 provided an empirical evidence of the signification to address ECs through developing a better specification at the start of the product development process, as well as to increase the understanding about the nature of changes in specification after the design process is completed. The *document analysis* (specification document) of Study 3 provided an insight of the process that design engineers do to understand the design problem during the task clarification process (specification development). The *interviews* of Study 2 provided an understanding the way design engineers do to go about specification development and the management of requirement changes during the design phase.

Selection of methods for empirical studies relies on many factors. In general, it can be divided into two categories: 1) controlled and 2) uncontrolled factors. The controlled factors may include; the research objectives, the research questions, the research approaches and the research paradigm. The uncontrolled factors include; accessibility to the company, the phenomena to be studied, the time available for the researcher and the stage of the design projects in the case study company.

To understand ECs and their relationship with the changes in specification in the real situation requires the researcher to follow a product development process from the start until the end of the process. The ideal method for data collection seems to be through direct observation of the product development process. However, to think about the best data collection method the research has to consider other factors, for instance the researcher has to consider the arena in which the research to be carried out. Several questions should be asked, e.g. do the companies willing to accept the researcher to carry out direct observation in their organisation? Does the company have suitable designs projects that can be followed by the researcher? How long is the duration of the project and does the researcher have enough time to follow the project? Additionally, the unintended possibility also necessary to be considered, for instance what happen if the phenomena the research want to observe does not occur during the observation process? What happens if the phenomena does occur but not in the group that the researcher is observing? The observation is limited access, as a researcher cannot observe more than one design groups at the same time. Even though direct observation seem an ideal data collection method in this research, it is not practical to this research study as the researcher has limited time to carry out the research. The practical methods are selected in this research study. Additionally, if you observe a product development process you only know of one product instead, methods to allow data on several projects in lesser depth were selected.

6.5 Recommendation for future works

The research has begun to understand the nature of specification changes during the product lifecycle’s phase. As a result, the significance of developing a better specification was empirically proved. The following areas have been identified for further research:

- The devised design method does not assist design students to identify the relationship between issues. Understanding the relationship between issues, and the capability of design engineers to describe the relationship between issues, would be beneficial to formulate better requirements and realize the objective of each requirement. Further development of the design method by assisting design students to identify the relationship between issues e.g. through ‘relationship matrix of issues’ would be a good idea for improvement.
- The research was carried out by analysing the available documentation in the companies. Since the research (Study 1) does not carried out with an active participation of industry thus some of the context of the document that was needed for clarification was not possible to obtain. Therefore, there is a need to carry out a document analysis with the active participation of the industry.
- The interviews were employed to understand how decision is made to includes a certain requirement into a specification. The interview method for data collection has some limitation as the information provided by the participants is limited to the information that the participants are able to articulate at the time of the interview. Thus, triangulation is required to support the weakness of one method to another method.
- Further evaluation of the support with design engineers based on the practical design problem is required as to prove that the support is able to facilitate design

engineers to produce better requirements (useful requirements) and a better specification (fewer changes). Thus, the tasks of the participants during the evaluation could be extended from the task clarification phase (formulating requirements) up to the conceptual design stage. The extension of the task is necessary to assess the implementation of requirements in the design successively to investigate the effectiveness of a good specification for changes mitigation.

- The literature review found that terminology within engineering design was used inconsistently and indicated the need for a clear definition. The terms ‘requirement’ and ‘specification’ were found to be particularly inconsistent. In addition, many ways to classify requirement were found that require further investigation in order to develop taxonomy of requirement in the engineering design domain. Additionally, the taxonomy of requirement will facilitate the development of a relationship matrix between issues and the type of requirement.
- Further research is required to investigate how the decision to include a certain requirement in a specification. From a number of verbal requirements, how the core requirements are produced and written in a specification? It could be beneficial to be shared with the novice design engineer as the task to develop a specification is knowledge and experience intensive. In addition, the relationship between verbal requirements and written requirements is required for further understanding for changes management.

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APPENDIX A

Interview Questions

The purpose of this interview is to collect experiences of design engineers in carrying out the design process, dealing with the specification, specification changes and customers. These experiences do not bind to the particular project but are general. Thus your contribution is very valuable and all your answers will be treated confidentially. The interview is about 1 hour and the interview session will be auditory recorded.

Interviewer: Mohd Nizam Bin Sudin
Interviewee:
Working experience:

Introduction
Can you introduce yourself?

To understand:
How was specification created?

1. *Can you explain what the project was about?(one of them);objective*
2. *Who was the customer of this project?*
3. *How did the customer approaches the company (IPU)?*
4. *Did they come with a set of specification? If yes, How detail was is? Formal or informal. If not, who develops the specification?*
5. *How were the contents of specification derived? What are the major elements in the specification?*
6. *How do you ensure the clarity of the specification statement?*
7. *Do you have any own procedure to develop the specification? If yes, can you sketch it? If no, what was your references?*
8. *Do you give the specification to your customers? Do you get their feedback?*

How was specification used?

1. *How many design engineer (in IPU) involves in this project? Is the specification distributed to them?*
2. *How do you carry out the design process? Do you start after the specification is drawn?*
3. *How do you consider (use) the specification while designing? Do you refer out? If so, why?*
4. *Did the specification help you while designing? If so what level or which phase of the process?*
5. *What types of specification have helped you? How?*

How was specification changed?

1. *How long is the project?*
2. *Have you experienced specification changes? How does it start? Who initiate it?*
3. *What do you understand about specification changes? Modify, add, delete, or change the value?*
4. *It the majority of cases, was the specification changes are directly requested? Or the specification was affected by the other charges?*
5. *Do you have any examples? Can you explain it?*

6. *Do you record all the specification changes? Why?*
7. *When does it happen? How about its impact?*
8. *How do you trace the impact of specification changes?*

Starting-introduction
I am Mohd Nizam, A PhD student in the DTU MAN, I was started my study in Nov. 2007. My research is about engineering change and specification-the relation between them. This interview aims to understand about how was specification created? How was specification used? And how was specification change during the product development process?

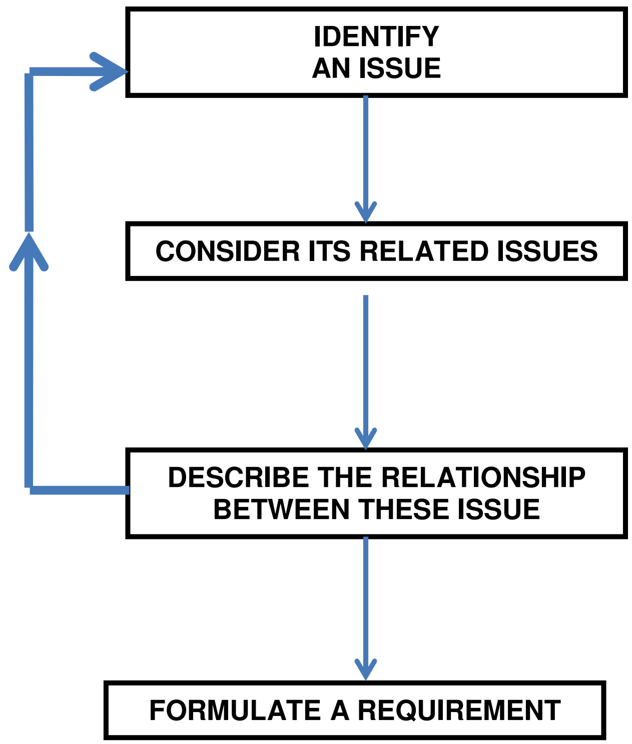
I am sure that you have involved in many projects since you are here, maybe some of them are in the progress whereas some of them were completed. Out of many projects that you have involved, can you explain one of them?

APPENDIX B

Design Support Booklet

Table of Content

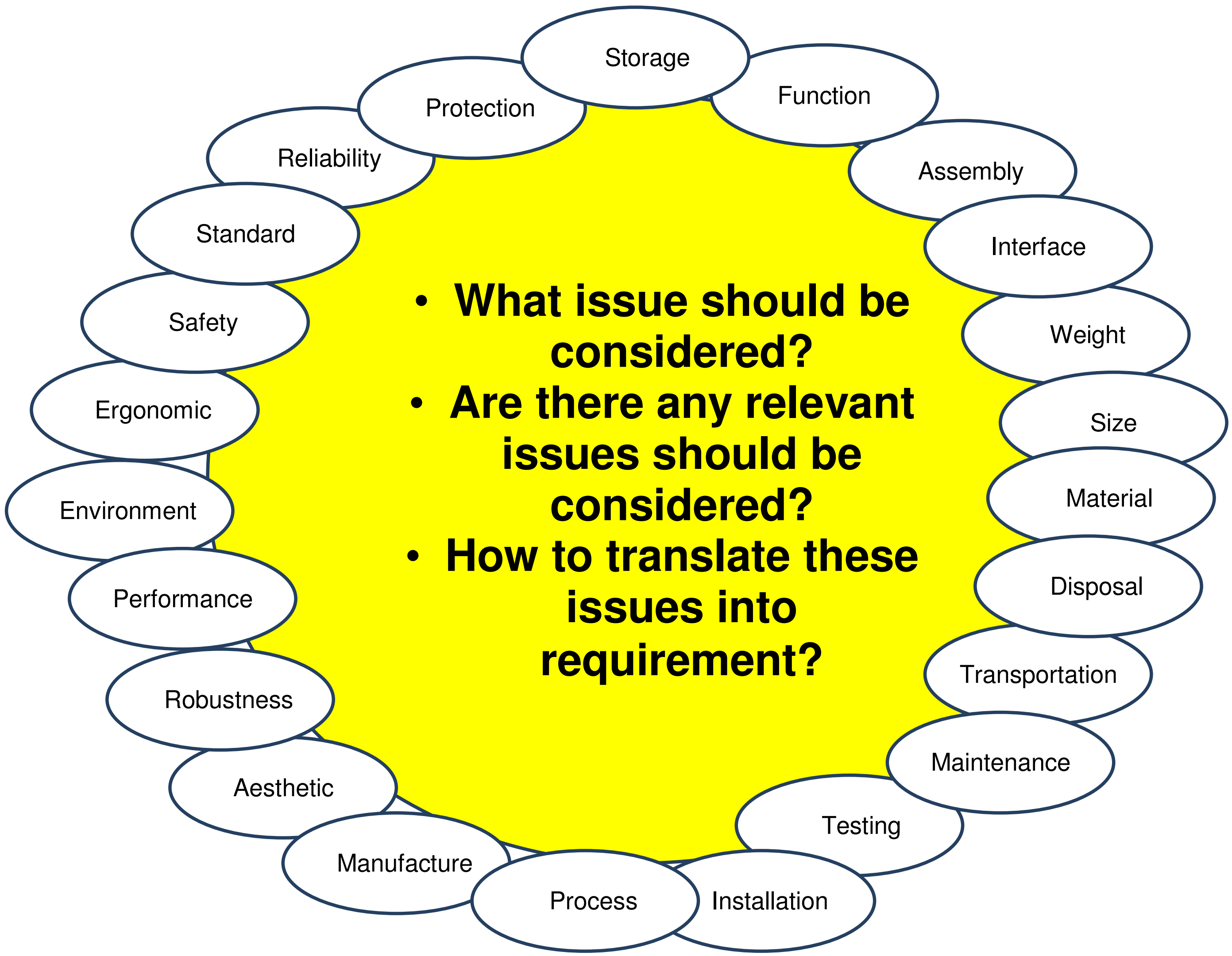
Requirement Formulation Method



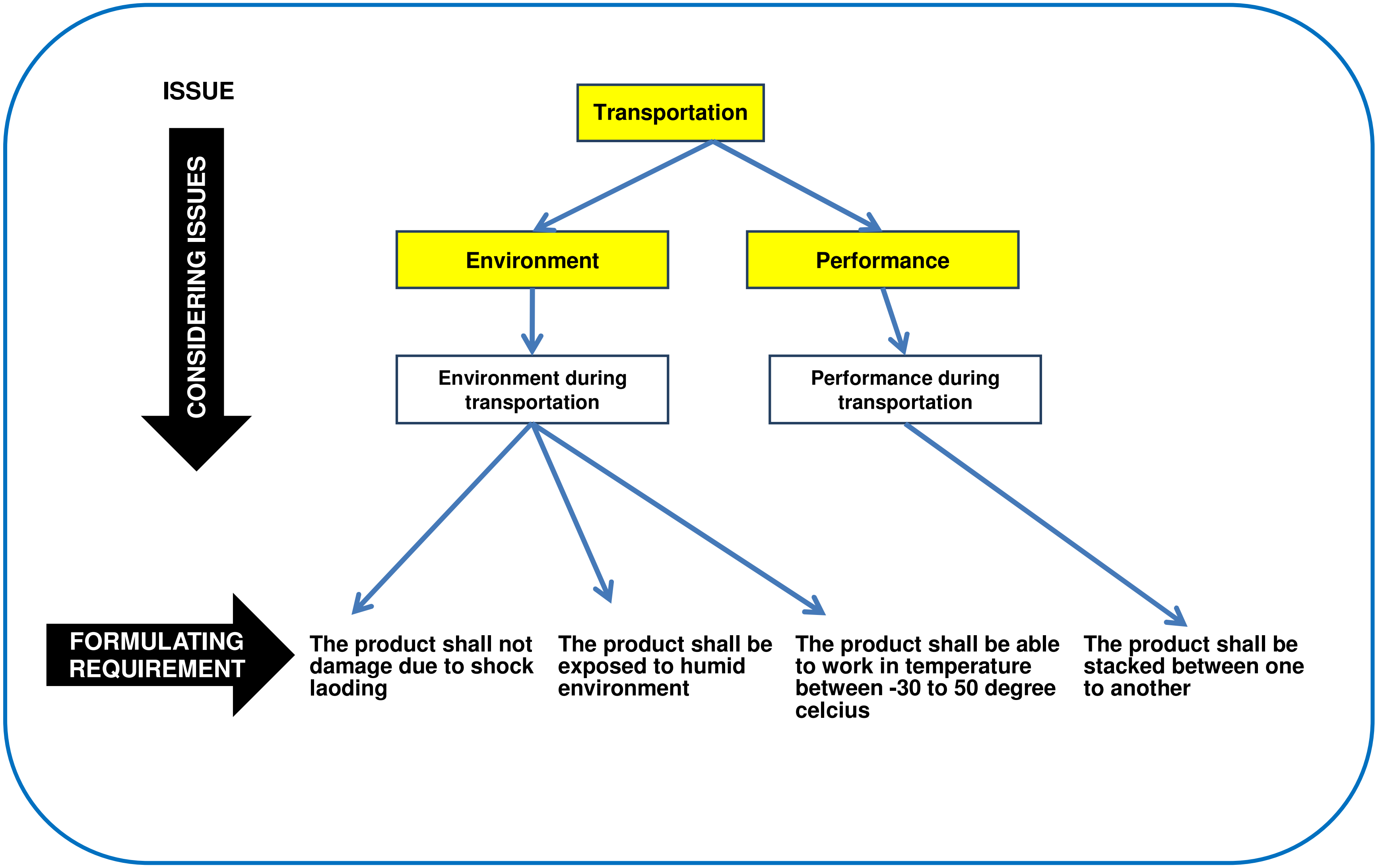
HOW TO USE THE METHOD

1) Chose ONE ISSUE from the list (refer to page 3) that is important for developing the product
2) Identify ITS RELATED ISSUE from the list (refer to page 3)
3) CONSIDER BOTH ISSUES and define the relationship between these issues
4) Translate these issue into a requirement (refer to page 4)
5) Go to step 2 (identify other related issues, IF ANY)-refer to page 4
6) Proceed to step 3 and 4
7) Chose ANOTHER ISSUE from the list and repeat this process (refer to page 4).

LIST OF ISSUES



USE OF METHOD-EXAMPLE



GLOSSARY OF ISSUE

Issue	Explanation
Function	**Function:** Describe the product's desired behaviour
Environment	**Environment**: to which environmental influences is the product subjected during development and use.
Weight	**Weight**: Do production, transport, or use put limits as to maximum weight?
Size	**Size**: Do production, transport, or use put limits as to maximum dimension?
Material	**Material**: Are special material necessary? Are certain materials not to be used (for example in connection with safety or environmental effects
Ergonomic	**Ergonomic**: Deals with the characteristics, abilities and needs of humans and, in particular, the interfaces between humans and technical products.
Aesthetic	**Aesthetic**: What are the preferences of the consumer, customer? Should the product fit in with a product line or houses style?

Performance	**Performance**: What are the parameter by which the functional characteristics will be assessed (speed, power, strength, accuracy, capacity, etc.)
Reliability	**Reliability**: How large may ‘mean times before failure’ and mean times to repair’ be? Which failure modes, and resulting effects on functioning, should not certainly occur?
Robustness	**Robustness:** The quality of being able to withstand stresses, pressures, or changes in procedure or circumstance.
Issue	**Explanation**
Safety	**Safety**: How safe the product to the user during operation, service, emergency, failure, handling, transportation, assembly, installation, etc.)
Protection	**Protection**: is packaging required? Against which influences should the packaging protect the product?
Standard	**Standard:** Which standard (national and international) apply to the product and its production? Should standardization within the company or industrial branch be taken into account?
Manufacture	**Manufacturing**: should the product be designed for existing facilities; are investments in new manufacturing facilities possible? Is (a part of) the production going to be contracted out?
Assembly	**Assembly:** Should the product be designed for existing facilities; are investments in new assembly facilities possible? Is (a part of) the production going to be contacted out?

Testing	**Testing**: What kind of functional and quality tests the product submitted, within and outside the company?
Transportation	**Transportation**: what are requirements of transport during production and to the location of use?
Storage	**Storage**: Are there during production, distribution, and use (long) periods of time in which the product is stored? Does this require specific ‘conservative’ measures?
Installation	**Installation**: Which requirements are set by final installation outside the factory
Maintenance	**Maintenance**: Is maintenance necessary and available? Which part has to be accessible?
Disposal	**Disposal**: It is possible to prolong the materials cycle by re-use of materials and parts? Can the materials and parts be separated for waste disposal?
Interface	**Interface:** Physical connection between artefact to artefact
Process	**Process**: The way an action is done e.g. the installation process of product, transportation process of product, etc.
Protection	**Protection**: Type of protection to product to avoid any damage during human action to the product e.g. transport, maintenance, etc.

APPENDIX C

EVALUATION FORM FOR THE DESIGN SUPPORT

Name:	**Position:** **Working experience:**
Q1.What did you think (learn) about this support?	
Q2.How easy is the support to use?	
Q3.Is there any change in your behaviour when using this support?	

Q4.What did you please about this support?
Q5.Did you consider issue and its related issues to decompose design problem previously?

APPENDIX D

ASSIGNMENT
DURATION: 1.5 Hours

HiAdventure Inc. Is a fairly large US firm (some 2000 employees) making backpacks and other hiking gear. They have been very successful over the last ten years, and are well known nationwide for making some of the best external-frame backpack around. Their best selling backpack, the midrange HiStar, is also sold in Europe.

In the last one and a half year, this European activity has suffered some setbacks in the market.

On the basis of this marketing report, HiAdventure has decided to develop an accessory for the HiStar.

> A special carrying/fastening device that would enable you to fasten and carry the backpack on the mountain bikes
>
> The device would have to fit on most touring-and mountain bikes and should fold down or at any rate be stacked easily
>
> A quick survey has shown that there is nothing like this on the european market.

The idea is particularly interesting for HiAdventure, because the director Mr Christiansen has a long standing private association with one of the chief product managers at the Batavus bicycle company (one of the larger bicycle manufacturer in northern Europe, based in Holland). Mr Christiansen sees this as a good opportunity to strike up a cooperation and profit from the European marketing capacities of Batavus.

Batavus product manager, Mr Lemmens is very enthusiastics about putting a combination-product on the market, a mountainbike and backpack that can be fastened to it. The idea is to base the combination-product on the Batavus Buster (a mid range mountainbike) and sell it under the name Batavus HikeStar

The design department at Betavus has made a preliminary design for the carrying/fastening device, but both Mr Christensen and Mr Lemmens are not very content with it, the user's test performed on the prototype also showed some serious shortcommings.

You are hired by HiAdventure to make a specification of the device.

MARKETING RESEARCH

Summary of the results

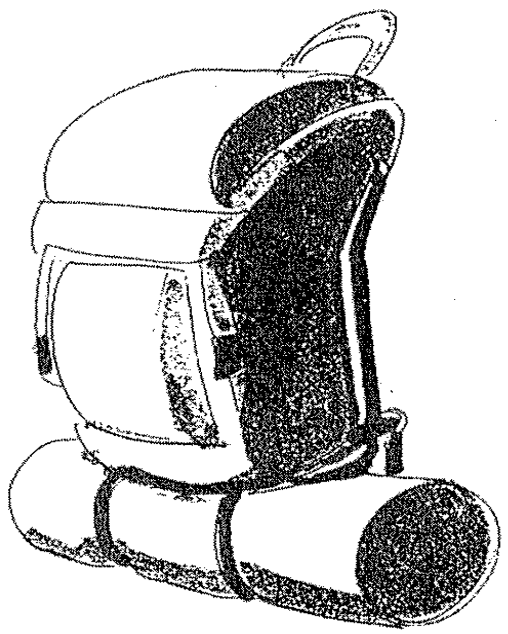
- A new holiday pattern is comming up: more and more people choose an active vacation in which both bike riding and hiking are being performed. On the whole, longer trips by bicycle are alternated by shorter trips by foot
- Until now, this has been limited to organised-and group travel, because of the difficulties in organising such a journey (renting bikes, transport of the luggage, etc)
- This new holiday trend is especially popular among young people, ages 21-35 who have been taking active in holiday before, they visit europes' mountains regions, including French Alps and the Pyrenees. The ratio male/female is estimated at 5/3
- The target group is estimated at 250, 000 people

USE OF BACKPACK

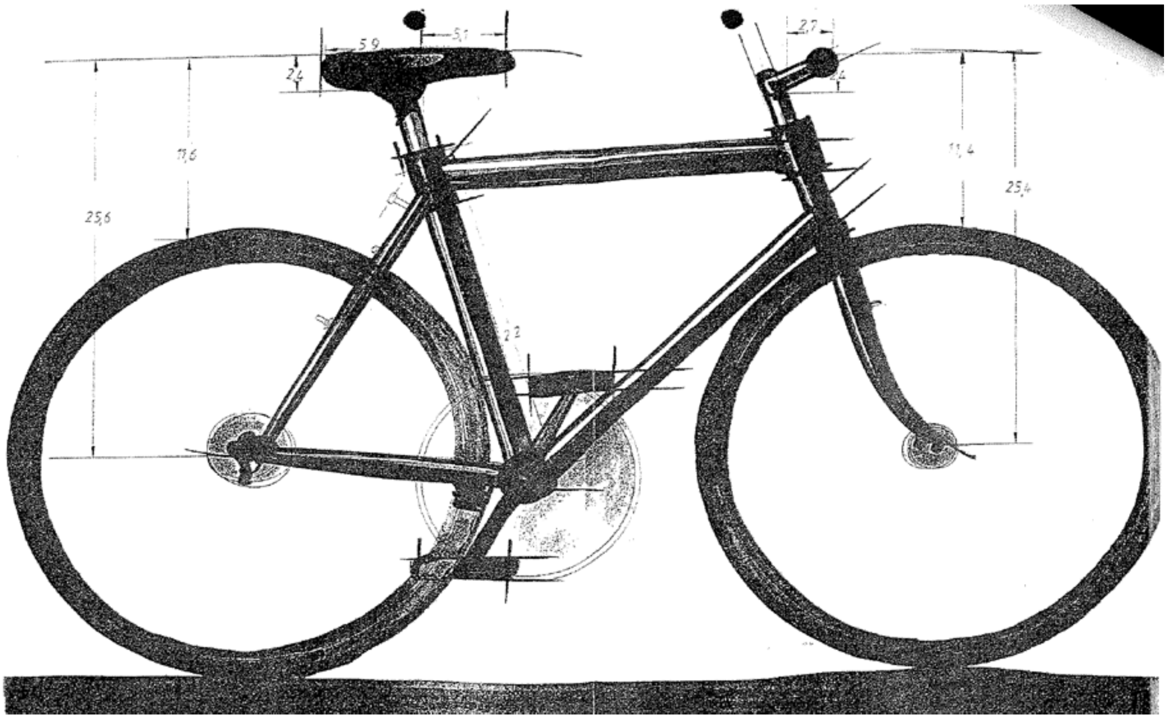
The HiStar given to you and show in the drawing the small, 40 liter backpack. The larger, 55 and 65 liter versions have the same layout and frame width, but they are longer

Backpack for hikes like these normally contain up to 22 kg of luggage, including a sleepping back and mattress

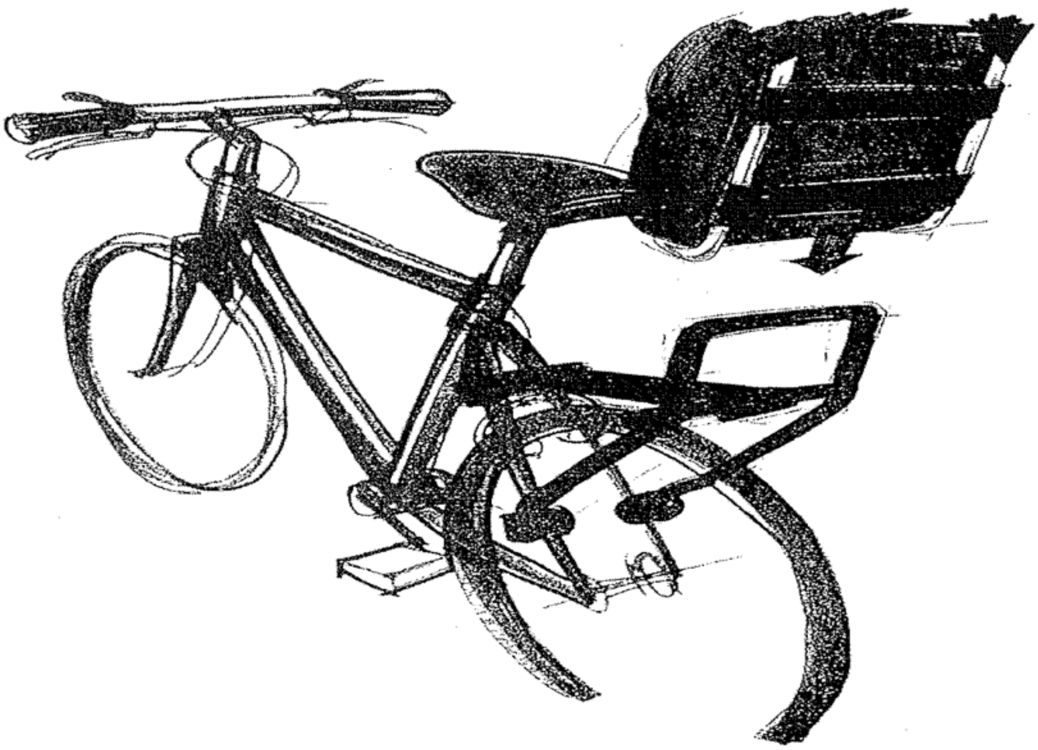
Four extra straps are supplied with each backpack. These straps can be used to attached extra luggage to the sides or bottom of the HiStar. For Instance (see picture).



BETAVUS DESIGN-MOUNTAINBIKE



BETAVUS DESIGN



APPENDIX E

EG4-S

Q1. What did you think (learn) about this support?

Answer: The provided support is very useful as it provides a clear method on how to translate an issue to requirement statements. Without the support the process of translating issues into requirements will definitely be more difficult and hard. Overall this support really helps and guided me during the task.

Q2. How easy is the support to use?

Answer: The support is very easy to use because the organization of support is very clear as the step by step method is represented in the flow chart. For the issue given in the support, they are represented in the form of small circles which is very interesting and clearly understand. The overall comment is the support was very easy to use.

Q3. Is there any change in your behavior when using this support?

Answer: When I am using this support there are slightly change of my behavior. Using the support I became more motivated and inspired to complete the task. This support has changed my perception before I was given the task. Before starting the task I am worry that this task is difficult. After reading the support I am very happy and motivated.

Q4. What did you like about this support?

Answer: The things or criteria that make me please with this support are the structure of the support which is very attractive and easy for me to understand. The explanation and the given examples are simple which make me easy to complete the task.

Q5. Did you consider issues and its related issues to carry out task clarification process previously?

Answer: Previously, the issue and related issue are also considered but not very detailed as I was given the support. With the support, issue and related issue is explained in detail

The study focuses on the nature of changes of specifications and engineering changes in the product development process. The underlying reason for engineering changes is changes in specifications and theses changes occur either to improve the product being designed or to correct errors. Engineering changes occur at any stage during the product development, and these changes have negative impact on time and cost of the process. The objective of the study is twofold: Firstly, to establish and empirical based understanding of the significance of specification changes to engineering changes. Secondly, to develop a practical support to facilitate design engineers to formulate better specification for the product being design. The results of the three empirical studies justify the need of supporting methods and tools for formulating and compiling specifications in the early phase of product development.

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